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A MODULAR DESIGN APPROACH TO SUPPORT SUSTAINABLE DESIGN

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ABSTRACT

This paper presents a redesign method supporting sustainable design of products. The method correlates product modularity with various life cycle directions at the conceptual stage of design. In the case of product redesign, the modular design approach allows designers to focus on increasing the sustainability of a product in terms of recyclability, disassembly and reduction of resource usage at the conceptual stage. By stepping back to the conceptual design phase and analyzing the product free from its current embodiment solutions, the scope of redesign and the potential product improvement increases. At this stage of design, the comprehension of the relationship between the various life cycle aspects of the product and the product design is essential. The elimination preference index (EPI) metric, calculated by pair-wise comparison of various factors governing the product design, quantifies the effect of redesign alternatives on product sustainability. The method is applied to the redesign of twelve small-scale consumer products, of which one example is presented here. In all cases, the redesigned products exhibited enhancement in modularity and part count reduction.

Keywords: Sustainable design, modularity, life cycle assessment.

1. INTRODUCTION

Sustainable design defined broadly is the problem of designing environmentally benign products so that the environment can be maintained with minimal negative effects from the product throughout the product's entire lifecycle. The work presented in this paper shows one avenue as to how sustainable design can be achieved at the conceptual design stage. Although sustainability encompasses a vast number of issues ranging from energy efficient solutions, design for disassembly, recycling, proper material selection, and improved manufacturing choices, the research focus of this paper examines the link between product modularity and sustainable products.

In sustainable design, the end goal is the creation of an artifact, product, system, or process that fulfills some functional requirements at some desired level of performance, including the functional requirements of "no-impact" on the environment. Traditionally, engineers identify how to measure product performance, model and assess the performance of a design concept with respect to that performance measure and address changes to the design to achieve the desired level of performance. This measure, model, assess, and address loop is always challenging, and developing sustainable product concepts magnifies this challenge. For instance, how does the designer measure the sustainability of a concept that may be little more than a sketch and listing of solution principles for critical functionality? How does the designer assess sustainability at this design stage? Then, with an assessment of sustainability at hand, how does the designer change the concept to improve sustainability?

When compared to non-modular designs, modular consumer products often exhibit advantages such as reduced assembly time, part number minimization [Bremmer, 1999 & 2000], and ease in disassembly and recycling [Viswanathan and Allada, 2000]. The relationship between specific aspects like recyclability and modularity has been extensively analyzed, but often without reasonable attention to other features such as dismantleability, serviceability, assembly, and human factors [Marks, et al., 1993; Viswanathan and Allada, 2000; Ishii, 1998]. Product development objectives vary to a large extent with market scenario, nature of the product, manufacturing methods, economic feasibility, and time to market. Focusing only on one particular aspect is not a versatile proposition in such situations. A multi-objective approach to improve the total life cycle impacts of a product is needed. We propose a methodology to incorporate multiple design features into modular redesign as well as in new design. The following sections present a review of the product representation and design tools that have been used in this paper. We then present our new methodology and illustrate its effective use in redesign.

2. REVIEW OF RELATED WORK

We turn next to a review of the state of the art in area of sustainable design and the areas that support sustainable design. In particular, we first review product function representation schemes and modular design approaches.

2-1. REPRESENTING PRODUCT FUNCTION

Perhaps the most difficult and critical phase of engineering design is the fuzzy front-end of the process known as conceptual design. This difficulty is due in part, perhaps, to the evolving strategies and methodologies that exist for this phase of design. However, over the past few decades, design methods have matured and systematic approaches to conceptual design have emerged [Pahl and Beitz, 1988; Suh, 1990; Ulrich and Eppinger, 1995; Otto and Wood, 2001]. In particular, the systematic approach of Pahl and Beitz and Hubka [Hubka, 1984], representing European schools of design, has spawned variant methodologies in American design literature [Ullman, 1997; Ulrich and Eppinger, 1995; Otto and Wood, 2001]. Regardless of the methodology variation, all begin by formulating the overall product function and breaking it into small, easily solved sub-functions. Solutions to the sub-functions are sought and the form of the device then follows from the assembly of all sub-function solutions.

Standardized representations of product function have been studied to enable a systematic approach to functional modeling [Hundal, 1990; Koch, et al., 1994; Malmqvist, et al., 1996; Altshuller, 1984; Kirschman and Fadel, 1998; Kitamura and Mizoguchi, 1998 & 1999; Umeda and Tomiyama, 1997; Sasajima, et al., 1995; Little, et al., 1997; Otto and Wood, 1997; Stone and Wood, 1999; Murdock, et al., 1997; Szykman, et al., 1999; Hirtz, et al., 2002]. The result of these recent efforts is a design language known as the Functional Basis [Hirtz, et al., 2002]. The functional basis uses function and flow words to form a sub-function description as a function and a flow (i.e., a verb-object format). The functional basis is intended to be broad enough to span the entire mechanical design space while not being repetitive. Generation of a black box model, creation of function chains for each input flow, and aggregation of function chains into a functional model are the sequence of steps that lead to the repeatable formation of a

functional model in their approach [McAdams, et al., 1998; Kurfman, et al., 2001]. To briefly illustrate this technique, the black box model and functional model of a cup are shown in Figure 1. The black box model is constructed based on the overall product function and includes the various energy, material, and signal flows involved in the global functioning of the product. The functional model is then built from sub-functions that operate on the flows listed in the black box model.
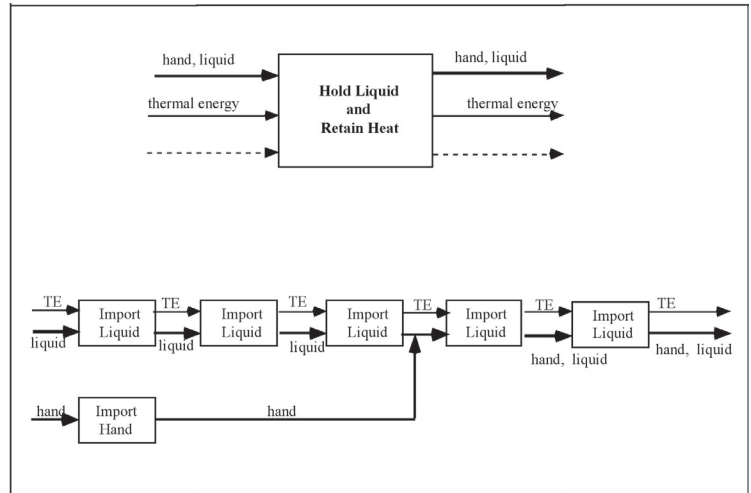

Figure 1: Black box model and functional model of a cup.

Functional models for any product can be generated using this technique. Repeatability, ease in storing and sharing design information, and increased scope in the search for solutions and module identification are some of the advantages of these functional models [Stone and Wood, 2000]. Functional models reveal functional and flow dependencies and hence are suited for module identification [Stone, et al., 2000]. Functional representations also increase the clarity of the design problem and tracking of input and output flows [Pahl and Beitz, 1988].

McAdams, et al. described a matrix-based technique that is used to quantify and share product information communicated in the functional models, thereby aiding in design by analogy and component reuse [McAdams, et al., 1999]. Yu, et al. have studied the impact of customer need analysis in defining product architecture [Yu, et al., 1998]. Stone, et al. discussed quantitative functional models based on customer need associations to sub-functions in the functional model. This led to the development of a product-function matrix that helps in identifying groups of products performing similar functions [Stone, et al., 2000]. The authors suggested examining sub-function commonality to identify similar products. In addition, Dahmus, et al. presented an approach to identify a family of products that share modules based on a study of shared and unique functions [Dahmus, et al., 2000]. This review supports the usefulness of functional models not only as a valuable product representation tool but also as a method of communicating and storing product design data.

2-2. MODULARITY

Modular products offer several advantages. Product customization, lead-time reduction, component production economy, and ease of maintenance and repair are some noted benefits of modularity. A modular product is defined as a product composed

of distinct part groupings that perform a single function or group of functions. Huang and Kuisak defined product modularity as the creation of product variants out of common units, and they described modules as independent, standard, and interchangeable units that satisfy a specific set of functions [Huang and Kuisak, 1996]. Huang and Kusiak also described graph and matrix based methods to identify clusters of components in a product that are strongly connected by transmission of energy or material. Modular products have minimal interaction between components and have similar physical and functional architecture [Stone, et al., 2000; Ulrich and Tung, 1991]. Modules defined by the energy, material, and signal flows in the product assist the transformation from the conceptual to the embodiment stage of design [Pahl and Beitz, 1988]. Identifying the similarities in and minimizing component interactions are the purpose of realizing modularity in products. Marks, et al. stated that components in a part should be grouped according to the various life cycle aspects of the product and presented a computer-based graphical tool to identify modules in a product and enhance recyclability [Marks, et al., 1993]. In an effort to codify module identification at a functional level, Stone, et al. presented a set of three heuristics to identify modules from the functional model [Kurfman, et al., 2001]. The three heuristics are comprised of two flow-based rules (dominant flow heuristic and branching flow heuristic) and one function-based rule (the conversion-transmission heuristic). For a majority of products, modularity plays an important role in determining assembly, service, disassembly, recycling, and other such life cycle characteristics [Coulter, et al., 1998]. Modularity is highly beneficial across many life cycle viewpoints; this furthers the need to achieve improved modularity in products.

2-3. SUSTAINABLE DESIGN

Research that enables the design of sustainable products has covered much ground. Nevertheless, a seamless and comprehensive integration of sustainability issues into both educational design curriculum and industry practice has not yet been accomplished [Rocha and Brezet, 1999]. Generally, approaches such as eco-design, green design, and Design for the Environment (DFE) are aimed at achieving sustainable products by shifting the traditional design process to thoroughly account for environmental issues. The objective is to promote a holistic view of a product that includes consideration of all phases of a product from inception through its own teardown and reuse [Hundal 2002; Ehrenfeld, 2001].

One guiding principle of DFE is to minimize energy and material usage while at the same time maximize product life and reuse [Cowell and Hodgson, 2000; Mackenzie, 1997]. This basic strategy leads to a focused approach of maximizing both product durability and flexibility as a directed means for innovating sustainable designs. To achieve these goals, designers have high-level principles that codify general sustainability knowledge. For example, the twelve principles of green engineering address general goals that should be sought during design [McDonough, et al., 2003]. Though these guidelines are useful, there is still a lack of systematic design methods for sustainable design that can be applied at the conceptual design stage. In order to provide more direction, several techniques have adopted a Life Cycle Assessment (LCA) approach [Glazebrook, et al., 2000]. LCA is an analysis approach that generally takes the form of checklists, indices, matrices and the interpretation of their results [Cowell and Hodgson, 2000; Otto and Wood, 2001]. The procedure for an LCA of a product involves three steps: inventory analysis, impact analysis, and improvement analysis [Conway-Schempf and Hendrickson, 2002]. One weak point of LCA is the time intensive nature of collecting information that sufficiently describes the lifecycle [Anderl, et al., 2002]. Additionally, the uncertainty involved in impact assessment due to the complexity of a total life cycle perspective is problematic in practice [Hersh, 1997]. In order to address these concerns a technique for making an approximate lifecycle assessment has been proposed [Eisenhard, et al., 2000]

One approach to integrating sustainable design into the design process is the use of modeling and optimization routines which can be applied along with other existing analytical tools which engineers regularly use [Thurston and Srinivasan, 2003; Hula, et al., 2003]. This integration offers a powerful aid as an analytical device and visualization tool for design tradeoffs such as the problem of maximizing positive environmental effects while minimizing cost. Another technique based on Quality Function Deployment (QFD) provides a means of relating parts and concepts to environmental issues in an analogous format to customer needs in the traditional QFD [Masui, et al., 2002]. While these techniques are appropriate, they are somewhat limited to embodiment and detailed design. However, Lagerstedt has proposed an extended functional product representation that helps designers balance traditional product performance requirements with environmental needs in the early stages of design [Lagerstedt, et al., 2003, Lagerstedt, 2003]. Similarly, a method for incorporating customer preferences into a decision model was created to assist in making tradeoff decisions between customer needs and environmental concerns [Thurston and Hoffman, 1999].

Some prior work has focused on product structure, configuration, and modularity as it relates to sustainability [Luttrupp, et al., 2002]. The use of a fuzzy graph for analyzing the similarity of design elements according to the compatibility of usage life, technology life, and material helps to incorporate sustainability issues into modularity choices [Qian and Zhang, 2003]. A technique for evaluating the effect of product configurations on the end-of-life disassembly of products was developed to address the value of configurations at the end of their service life [Viswanathan and Allada, 2000]. Design Structure Matices have been used to segment components based on recyclable content [Newcomb, et al., 1998]. In general, synthesis of solutions during conceptual design involves the identification and connected arrangement of both functions and their physical solutions [Chakrabarti, 2002; Antonsson and Cagan, 2001]. Understanding how this can be accomplished to form flexible and durable products remains a problem.

2-4. SUMMARY

In this paper, a new approach to enhance product modularity and simultaneously track the indicators of the effects the design changes impose on the numerous aspects of the product is presented. Product redesign is realized from a functional standpoint allowing life cycle factors to be addressed early in the design stage. This quantification scheme may also be used as a design by analogy tool by creating a database of the product information.

3. PROPOSED METHOD

The goal of the method presented here is a redesign tool that both reduces part count and improves the life cycle impact of the product. These goals are achieved through developing a modular architecture for the product. The life cycle factors we will focus on include assembly time, part necessity, ease of component handling and manipulation, ease of component insertion for assembly, recyclability, and dismantleability. Proposed is a new quantitative metric for life cycle assessment. The EPI accounts for several key life cycle factors of the design. Components with high EPI values will be candidates for elimination. In addition, during redesign, an attempt is made to find components that have low EPI and potential to solve multiple functions thus improving overall environmental impact.

3-1. RELATING LIFE CYCLE FACTORS TO THE ELIMINATION PREFERENCE INDEX (EPI)

The EPI represents the designer's preference for removing a part from a design based on various life cycle factors. The EPI is a representation of environmental impact that allows the designer to reason about approaches to improving the design. The normalized value accounts for multiple design factors and enables comparison of components and identification of the best embodiment solutions for similar modules and sub-functions between products. In general, every aspect of the design has some environmental impact. Here, we focus on six factors with significant impact on the environment relevant to manual disassembly. In different cases or as better design for sustainability metrics are developed, factors can be included or excluded from the EPI calculation.

Table 1: Prioritized list of life cycle factors.

Factor	Priority
Assembly time	10
Part necessity	10
Dismantleability	7
Recyclability	5
Ease of handling	3
Ease of insertion	3

First, the relevant factors for the EPI are ranked and assigned an importance priority. For the purpose of illustrating the proposed technique, we have chosen the life cycle factors presented in Table 1. The EPI factors chosen are based on subjective values of the designer, but, once codified, they are treated consistently throughout the remainder of the method presented.

In a scenario relevant to the redesign of a consumer product, each factor was assigned a priority value from 1 (low) to 10 (very high) based on the following reasoning.

• Assembly time – Assigned a very high priority value (10) to reflect the impact of reduced assembly time in cost savings for manually assembled products.

• Part necessity – Assigned a very high priority value (10) for cost-reduction potential from the identification of components that are nonessential and thus candidate for elimination.

• Dismantleability – Assigned a high priority value (7) to account for cost savings in reducing the time and difficulty of disassembling a component.

• Recyclability – Assigned a moderate priority value (5) for the reuse or recyclability of a component in the post-use stage of the product life cycle.

• Ease of handling/Ease of insertion – Assigned a low priority value (3) since both of these factors are strongly related to assembly time. These factors are included for the purpose of elaborating the proposed method.

Table 2: Standard pair-wise comparison matrix [Boothroyd and Dewhurst, 1983].

Priority	10-8 (very high)	8	8-6 (high)	6	6-4 (moderate)	4	4-2 (low)	2	2-0 (very low)
10-8 (very high)	1	2	3	4	5	6	7	8	9
8	1/2	1	2	3	4	5	6	7	8
8-6 (high)	1/3	1/2	1	2	3	4	5	6	7
6	1/4	1/3	1/2	1	2	3	4	5	6
6-4 (moderate)	1/5	1/4	1/3	1/2	1	2	3	4	5
4	1/6	1/5	1/4	1/3	1/2	1	2	3	4
4-2 (low)	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3
2	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2
2-0 (very low)	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1

From the prioritized list, the weight of each factor is computed by a simple mathematical pair-wise comparison [Saaty, 1980; Huang and Liao, 2000]. To reduce subjectivity and uncertainty, a standard ranking method, shown in Table 2, was used to correspond the relative importance, a_{ij}, of the ith factor to that of the jth factor.

Table 3: Pair-wise comparison values and weight of each factor.

Factor (Priority)	Assembly Time (10)	Part Necessity (10)	Dismantleability (7)	Recyclability (5)	Ease of Handling (3)	Ease of Insertion (3)	Weight
Assembly Time (10)	1	1	3	5	7	7	0.340
Part Necessity (10)	1	1	3	5	7	7	0.340
Dismantleability (7)	1/3	1/3	1	3	5	5	0.163
Recyclability (5)	1/5	1/5	1/3	1	3	3	0.081
Ease of Handling (3)	1/7	1/7	1/5	1/3	1	1	0.037
Ease of Insertion (3)	1/7	1/7	1/5	1/3	1	1	0.037

Based on the numerical priority values, the pair-wise comparison matrix, shown as the shaded part of Table 3, is derived from the standard pair-wise comparison matrix. The shaded comparison matrix demonstrates relative importance between the life cycle factors. For instance, assembly time is considered 7 times more important than ease of handling but only 3 times more important than dismantleability.

Next, the weight values for each life cycle factor, shown in the unshaded column of Table 3, are determined by normalizing the elements of the eigenvector corresponding to the maximum eigenvalue calculated from the pair-wise comparison matrix [Saaty, 1980; Huang and Liao, 2000]. Using the eigenvector assures consistency of the matrix and reduces inconsistency between the comparison values. These life cycle weights will be employed

during the final calculation of the EPI.

The next step is to quantify the life cycle factors for the product to be redesigned. The quantification methods for assembly time, part necessity (called part function by Boothroyed and Dewhurst), ease of insertion, and ease of handling are based on previous work presented in "Design for Manual Assembly" by Boothroyd and Dewhurst [Boothroyd and Dewhurst, 1983].

Assembly time is an estimate of the time required to grasp, manipulate, and assemble a part is obtained based on its shape and the processes involved in inserting and assembling the part. Assembly time is the sum of the time utilized in handling the part and securing it to the product.

Part necessity assesses the need for a separate part. The first three questions below have been adapted from Boothroyd and Dewhurst. The fourth was added in order to resolve certain issues that arose in the course of this study. The necessity of a part is assigned a 0 or 1 value based on the following questions.

1. During the operation of the product, does the part move relative to all other previously assembled parts?

2. Must the part be fabricated out of a different material?

3. Must the part be separate from all other parts in order to assemble or disassemble other separate parts?

4. Is the part absolutely essential for the flow of material, energy, or signal in the product?

If the answer to any of these questions is yes then the necessity value for the part is "0"; otherwise, the necessity for the part is "1" [Boothroyd and Dewhurst, 1983].

Plastic, molded parts, metal parts, and standard parts like screws and washers are some of the commonly occurring parts in consumer products. The quantification of recyclability of parts must be viewed from the available recycling and part reuse resources available to a particular company or market. Considering the extensive usage of plastic parts in the products, recycling plastics will be the focus of one such firm, while metals may be sold to other recyclers. Here, recyclability has been quantified on a scale of 1-4 (low to high rank of difficulty in finding a means to recycle a component) in the calculation of EPI, as shown in Table 4.

Table 4: Quantifying recyclability.

Type of parts	Recyclability
Screws and standard parts	1.0
Common plastics	2.0
Non-standard metal parts	3.0
Uncommon plastics	4.0

Dismantleability of a component must not only ascertain the ease with which a component can be removed from the product, but also account for the number of components and modules that can be disassembled following the removal of the component from the product. The method of calculating dismantleability is as follows.

1. Time to remove the component $\int$ Tp

2. Time to remove the fastener $\int$ Tf

3. Number of fasteners used to hold part in place $\int$ n

4. Special tools are required to dismantle the part $\int$ S = 1 if yes, 0 if no

5. Part is easy to insert $\int$ I = 1 if no, 0 if yes

For parts other than fasteners the value of dismantleability

will be calculated as:

$$Dismantleability = (n \times T_f) + T_p + S + I \qquad (1)$$

For fasteners and other such supporting parts,

1. Time to remove fastener $\int$ tp

2. Number of parts/assemblies that are opened up by removing fastener $\int$ N

3. Fastener head diameter and length are larger than 6 mm $\int$ L = 0 if yes, 1 if no

The dismantleability for fasteners will then be calculated as:

$$Dismantleability = \frac{t_p}{N} + L \qquad (2)$$

The final step in calculating the EPI is to combine the quantified life cycle factors into a metric that is comparable between components and modules. This step is accomplished by scaling the summation of the weighted factors by the maximum quantified life cycle value over the entire product, as shown in Equation 3.

$$\sum \frac{(QuantifiedFactorValue \times Weight)}{(MaxValueOfTheQuantifiedFactor)} \qquad (3)$$

The EPI encapsulates the life cycle factors deemed important in the product redesign and helps ensure that essential factors are not overlooked or de-emphasized in favor of less important factors.

Figure 2: Functional hierarchy and EPI based approach for redesign.
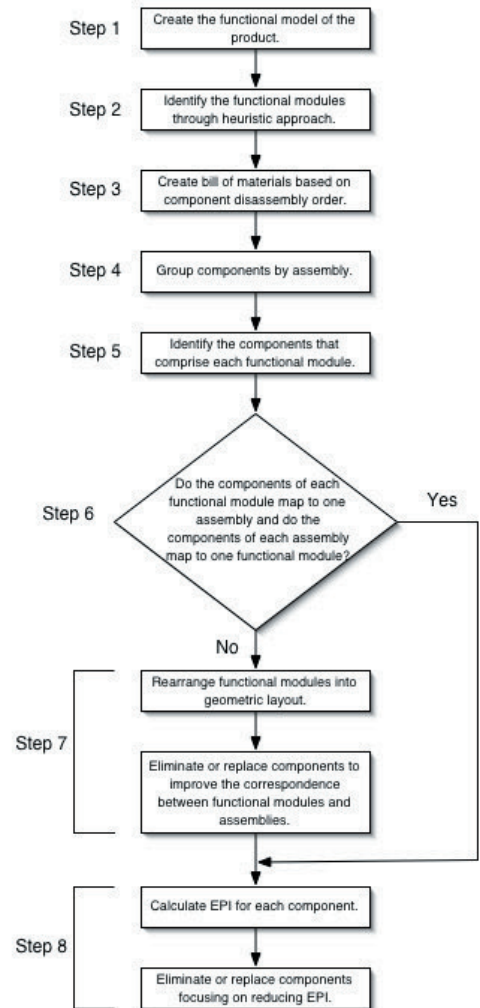
Normalizing the EPI enables EPI comparisons to be made between the components and modules of different products. The following section defines the procedure that employs the EPI to redesign a product for improved modularity and life cycle impact.

3-1. PROCEDURE

The design procedure presented here is developed in terms of a product redesign. Redesigning and improving existing products represents a large portion of product design. Extending the method to original design is a straightforward proposition, but an express treatment of such is beyond the scope of this paper.

The proposed strategy coordinates the EPI metric with a comparison of the functional modules and component assemblies to guide product redesign. Using established methods for the functional basis of design, the eight-step procedure for redesign (illustrated in Figure 2) is as follows:

1. Create the functional model of the product.

2. Group the functional model into functional modules based on the three heuristics described by Stone, et al. [Stone, et al., 2000].

3. Create a bill of materials in the order the components were disassembled.

4. Group the components by assembly. The components constituting one assembly are identified by a set of assembly operations that may be clustered together. Label the assemblies.

5. Identify the components constituting each functional module.

6. Using the information from steps 4 and 5, determine if a one-to-one mapping exists between the components comprising an assembly and the components that make up a functional module. In other words, do the physical subassemblies and modules correspond to those recommended by the functional heuristics? If components belonging to one assembly correspond to more than one functional module, redesign efforts should be directed at the component level to increase modularity. If components belonging to one function module correspond to multiple assemblies joined by an interface, redesign efforts should be directed toward eliminating the interface rather than components to increase modularity.

7. Rearrange the functional model to configure a rough geometric layout of functional modules. This arrangement is accomplished by grouping modules together such that the length of the flows between modules is reduced. In other words, the functional model is arranged such that it represents an efficient physical architecture. This rearrangement guides the designer toward feasible and efficient component configurations that help reduce the number of flows and flow interactions. Finally, the physical assemblies or modules are redesigned to correspond with the modules in the functional model. This redesign is focused on reducing the number of flows crossing each module interface, a goal achieved by usage of the module heuristics [Stone, et al., 2000].

8. Calculate the EPI based on pair-wise comparison weights and quantified life cycle factors. As shown in Equation 4, the functional module EPI (EPIfm) is generated from the summation of the component EPI values (EPIC) that constitute the functional module. The EPIfm can be used as a metric to rate the efficiency

$$EPI_{fm} = \sum EPI_C \qquad (4)$$

of the modules within a product.

The method of redesign detailed here was formulated through an empirical study of 12 consumer products. The following section discusses the method in detail as applied to one of the studied products, a Bissell hand vacuum. The product chosen is a purposefully simple example to provide a clean illustration of the proposed redesign method.

4. APPLICATION OF METHODOLOGY TO A BISSELL HAND VACUUM

The dismantled parts of a Bissell hand vacuum are shown in Figure 3. As the first step towards redesign of the product, the
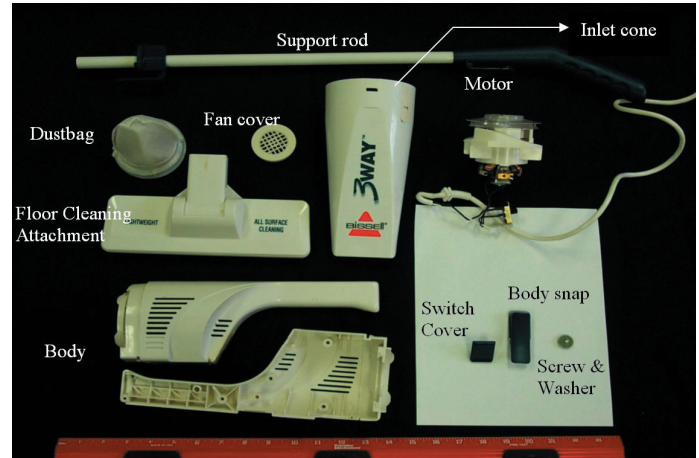

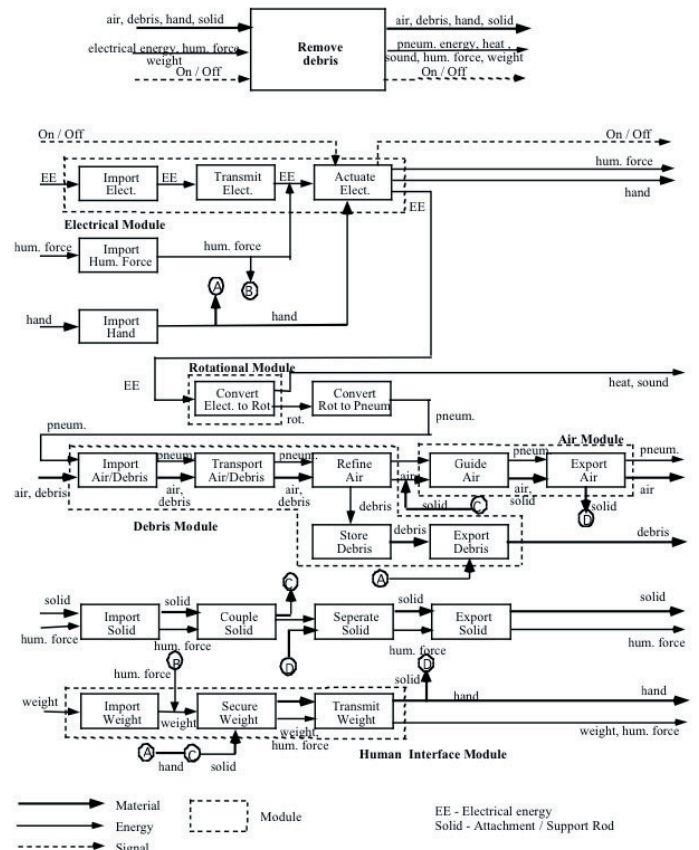**Figure 3: Exploded view of the Bissell hand vacuum.**

Figure 4: Black box and functional models of the Bissell hand vacuum.

functional model of the product was derived from the black box model using the functional model derivation method formulated by Stone and Wood [Stone and Wood, 2000].

The black box model represents the overall product function and the various input/output flows of energy, material, and signals. Each flow is followed from its point of entry into the product to its exit in order to generate the functional model. The transformations and operations performed on each flow are represented by verb-object pairs. The sub-function performed assumes the verb portion and the flow is the object. The black box model and functional model of the Bissell hand vacuum are shown in Figure 4.

Using the three heuristics described by Stone, et al. the functional modules present in the Bissell hand vacuum are the electrical module, the rotational module, the air module, the debris module, and the human interface module [Stone, et al., 2000]. The dotted lines shown in Figure 4 enclose the sub-functions of the functional model that are encapsulated by the identified functional modules.

The next step in the redesign process is the generation of the bill of materials based on the disassembly order of the components from the product. The bill of materials for the product is shown in Table 5. The list of components is grouped into assemblies, defined as product components (either a single part or a collection of parts) that may be removed from the product as one entity or in a single assembly operation.

Once the parts are grouped into assemblies, the assembly-functional module mapping of each product component is analyzed. As stated previously, if the number of assemblies is greater than the number of functional modules, the potential to reduce part count exists. If the components that make up a single assembly correspond to more than one functional module, the possibility of redesigning for improved modularity exists. Eleven assemblies were identified for the Bissell hand vacuum, but only five functional modules were defined from the functional model. This indicates that the modularity of the product could be improved through redesign.

Creating rough geometric layouts of the products using the

Table 5: Bill of materials for the Bissell hand vacuum.

| Assembly	Qty	Part Name	Function Performed	Description	Parameters
A1	1	Attachment for floor cleaning	Import Solid	Attaches to inlet cone & has brushes attached to it.	9" X 4" plastic with a hinged piece for attachment
A2	1	Inlet cone	Guide Gas/Import Gas/Import Solid	Holds the floor cleaning attachment.	plastic
	1	Dustbag	Store Solid	-	porous material
A3	1	Support rod for floor cleaning	Secure Weight	Attaches to body.	plastic rod 3/4" in diameter
A4	6	Screws to hold body together	Secure Weight	Holds body together.	1/2" screws
A5	1	Body snap	Secure Weight	Attaches inlet cone to the body.	plastic
	1	Right half body	Secure Weight	Encloses rotational and electrical module.	plastic
	1	End snap	Secure Weight	Holds body together.	plastic
A6	1	Switch	Actuate Electrical Energy	-	-
	1	Switch cover	-	Attaches to body and switch.	plastic
A7	3	Solders	Transmit Electrical Energy	-	-
A8	1	Plug & wires	Transmit Electrical Energy	-	-
	1	Screw to hold wire	-	Holds cord in place.	1/2" screw
	1	Washer	-	Holds cord in place.	-
A9	1	Fan	Convert Rotational Energy to Pneumatic Energy	-	plastic
	1	Nut	-	Attaches fan to motor.	brass, 1/4" hex head
A10	1	Motor assembly	Converts Electrical Energy to Rotational Energy	Johnson motor.	-
A11	1	Fan cover	-	Encloses the fan.	plastic disc with holes, 2" in diameter
	1	Left half body	Secure Weight	Encloses rotational and electrical module.	plastic
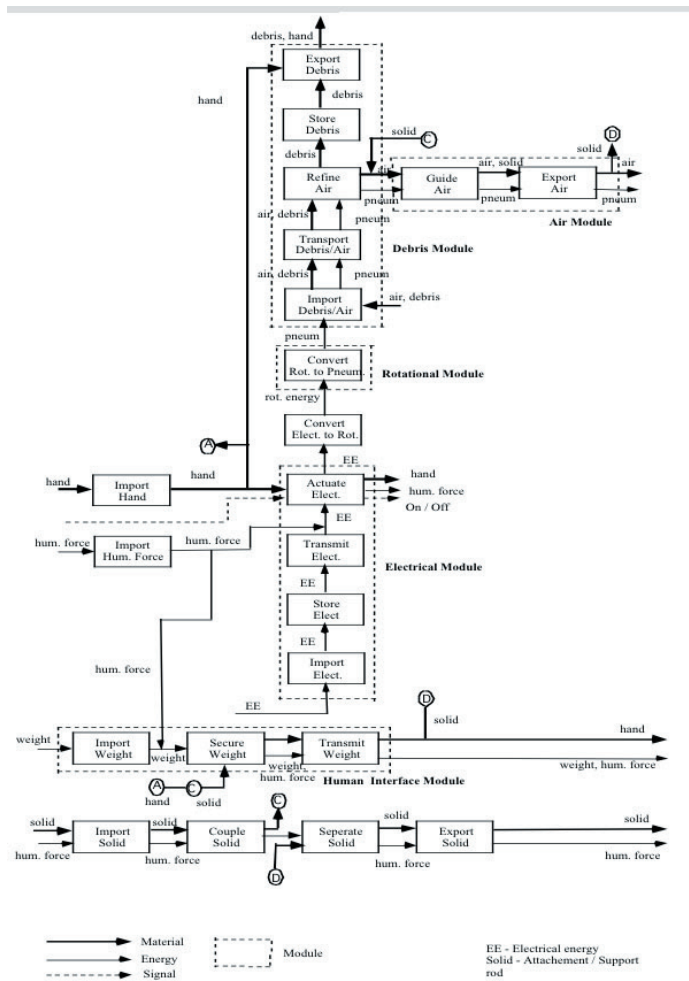
Figure 5: Module layout for the Bissell hand vacuum.

Table 6: Elimination Preference Index (EPI) chart for the Bissell hand vacuum.

Part Id	Qty	H	I	A	N	R	D	Part Name	EPI	Assembly	Functional Module
1	1	1.95	2	3.95	0	2	2	Attachment for floor cleaning	0.03	A1	Debris Module
2	1	1.95	6.5	8.45	0	2	9	Inlet cone	0.08	A2	Debris Module
3	1	1.5	1.5	3	0	4	1.5	Dustbag	0.03	A2	Debris Module
4	1	1.95	2	3.95	0	2	2	Support rod for floor cleaning	0.03	A3	Human Interface Module
5	6	2.25	8	61.5	1	1	30	Screws to hold body together	0.43	A4	Human Interface Module
6	1	1.95	2.5	4.45	1	2	2.5	Body snap	0.04	A5	Human Interface Module
7	1	1.95	10.5	12.5	0	2	13	Right half body	0.11	A5	Human Interface Module
8	1	1.13	1.5	2.63	1	2	1.5	End snap	0.03	A5	Human Interface Module
9	1	1.95	2.73	4.68	0	5	2.73	Switch	0.04	A6	Electrical Supply Module
10	1	1.95	5	6.95	1	2	5	Switch cover	0.06	A6	Electrical Supply Module
11	3	1.5	8	12.5	1	5	9	Solders	0.11	A7	Electrical Supply Module
12	1	1.13	4	5.13	0	5	9	Plug & wires	0.06	A8	Electrical Supply Module
13	1	1.8	4	5.8	1	1	4	Screw to hold wire	0.05	A8	Electrical Supply Module
14	1	1.13	4	5.13	1	4	4	Washer	0.05	A8	Electrical Supply Module
15	1	1.5	1.5	3	0	2	9	Fan	0.04	A9	Air Module
16	1	1.5	6.5	8	1	1	6.5	Nut	0.07	A9	Air Module
17	1	1.95	2.73	4.68	0	4	3.73	Motor assembly	0.04	A10	Rotational Module
18	1	1.5	1.5	3	1	2	1.5	Fan cover	0.03	A11	Debris Module
19	1	1.95	1.5	3.45	0	2	1.5	Left half body	0.03	A11	Human Interface Module
H - Manual Handling Time, I - Manual Insertion Time, A - Estimated Assembly Time, N - Part Necessity, R - Recyclability, D - Dismantleability											

functional module diagrams assists envisioning strategies for redesigning for modularity. The module layout shown in Figure 5 was generated from the functional model of the Bissell hand vacuum by following the path from the input of electrical energy to the point where debris are absorbed, stored, and exported. In this example, the human interface module is separate and hence can be positioned by choice.

The next step to aid in the redesign of the product would be to calculate the EPIC for each component in order to identify parts that warrant redesign and to substantiate redesign suggestions. The EPI chart for the Bissell hand vacuum is shown in Table 6.

The following section details the redesign suggestions generated for the Bissell hand vacuum using the tools described above to guide the redesign process.

4-1. REDESIGN POSSIBILITIES FOR A BISSELL HAND VACUUM

The debris module corresponds to assembly modules A1, A2, and A11 shown in Figure 6. The components that comprise the debris module cannot be eliminated or redesigned since they have a part necessity value of 0, implying that these parts are essential for the working of the product. Nor can these components be combined since they must remain separate for proper functioning of the product. If the body of the Bissell hand vacuum were designed to have a fine porous front end, the fan cover could potentially be eliminated. Eliminating the fan cover component would confine the debris module to assemblies A1 and A2, however, molding the fan cover to the body leads to difficulties in assembling the rotational module, electrical supply module, and air module. Redesigning the fan cover as a separate lid-like component and the body as a single molded plastic part would eliminate these difficulties.

Figure 6: Assemblies A1, A2, and A11 make up the debris module for the Bissell hand vacuum.

The human interface module shown in Figure 7 corresponds to components comprising assemblies A3, A4, A5, and A11. Since the support rod is a removable attachment, redesigning the two body pieces as a single molded piece that utilized press fits versus the body snap would eliminate a part from assembly 5 and remove the human interface module (the left half of the body) from assembly A11. The single body piece would also eliminate
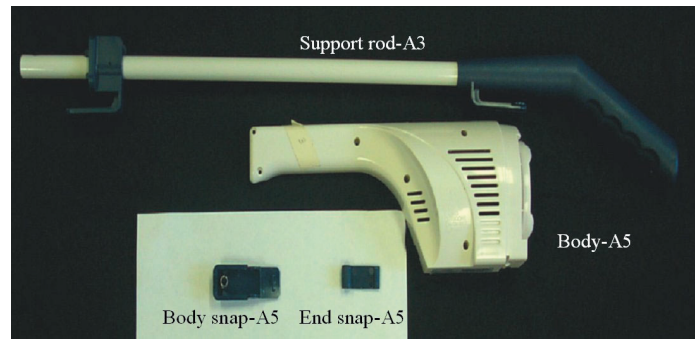

Figure 7: Assemblies A3, A4, and A11 make up the human interface module for the Bissell hand vacuum.

the need for the six screws required to hold the two body pieces together, thus removing assembly A4 from the product completely. These modifications would restrict the human interface module to two continuous assemblies, A3 and A5. This redesign would then require the assembly operations in this module to be ordered from the front end of the project. The end snap could also be eliminated and replaced with a sliding fit for the support rod. These design changes reduce the total EPI value of the human interface from 0.68 to 0.11 and the number of parts in the module from 10 to 2.
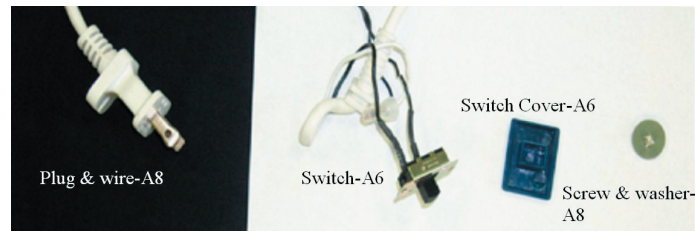

Figure 8: Assemblies A6, A7, and A8 make up the electrical supply module for the Bissell hand vacuum.

The electrical supply module corresponds to A6 through A8, shown in Figure 8. In the bill of materials, the switch cover is not associated with any function and has the highest EPI in the module. Therefore, this component is an immediate candidate for elimination. The screw and washer each with EPI values 0.05 can also be eliminated with little impact on the design. Additionally, assembly time can be reduced by conducting electricity to the motor through metal strips embedded on a plastic disc enclosure. These conducting metal strips would also enable a simple switch mechanism to actuate the electrical flow. This redesign would eliminate the need for soldering, making the module easier to assemble. These suggestions would reduce the EPI of the electrical supply module from 0.39 to 0.1, reduce part count from 6 to 2, and eliminates the time-costly soldering operation from the assembly.
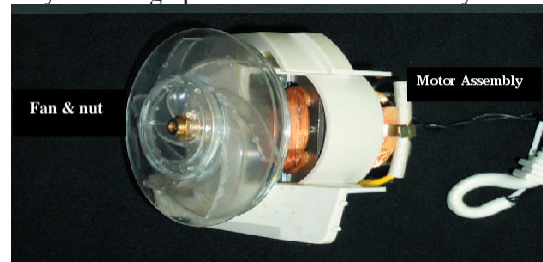

Figure 9: Assemblies A9 and A10 make up the air & rotational modules for the Bissell hand vacuum.

The air module is composed only of the fan and nut as shown in Figure 9. In this module, the nut can be eliminated and the fan designed to directly fit to the motor shaft via an interference fit. In order to accommodate these changes, the motor assembly would also require modification. The plastic disc enclosing the motor described in the redesign of the electrical module would play a vital role in supporting the rotational module through threads on the edges that mate with the body.

These suggested design changes, illustrated in Figure 10, are not only aimed at reducing EPI, but also at bringing the physical modules in tune with the module layout obtained by rearranging the functional model. Application of the proposed method of redesign overall reduces part count from 26 to 10 and effectively decreases the product EPI by 37%. The correspondence between assembly modules and functional modules after redesign also shows a considerable improvement in modularity.
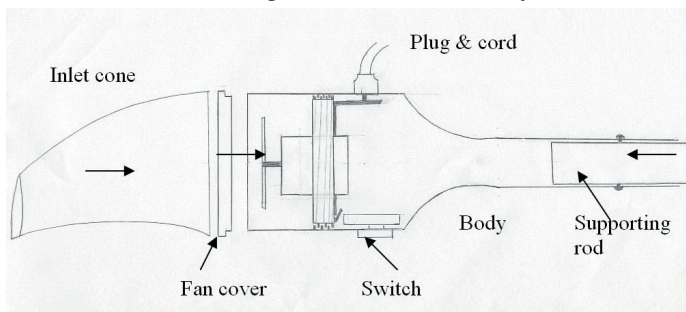

Figure 10: Redesigned Bissell hand vacuum.

5. CONCLUSIONS AND FUTURE WORK

The paper presents a redesign technique based on relationships between the functional modules and assemblies of a product. The redesign potential is quantified through the application of the proposed elimination preference index (EPI) metric. The applicability of the method is demonstrated through a redesign case study of a Bissell hand vacuum.

Initiated from the black box model, the technique begins with the generation of the functional model of the product using the functional basis language and flows of material, energy, and signals. Next, the functional modules are identified and the sub-functions rearranged to obtain module layout information. This step is followed by the quantification of six chosen aspects of product design using previous Design for Assembly techniques. The six aspects are then weighted using a pair-wise comparison technique. The strength of the method arises from the ability to associate the functional representation and assemblies of the product with life cycle information at the conceptual stage of design.

The redesign method is successfully applied a Bissell hand vacuum, demonstrating its effectiveness in enhancing modularity while emphasizing the incorporation of the various life-cycle aspects of the product into the redesign procedure. Further testing of the technique should be performed on medium and large-scale products to demonstrate robustness. Additionally, the relationship between EPI reduction and corresponding decrease in life-cycle costs should be analyzed to ensure a positive correlation.

Key contributions of this work include a development of the EPI which measures multiple life cycle impacts of a design. Included as part of the EPI as a measure that quantifies the disassembly of a product. Thus, designers can simultaneously consider design for manufacture and design or reuse during conceptual design. Also developed in this paper is a design method that combines the use of the EPI with modular design methods. Thus, the assembly and reuse advantages of modular architectures can be leveraged to create a sustainable design.

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