Proceedings of IDETC/CIE 2006
ASME 2006 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
September 10-13, 2006, Philadelphia, Pennsylvania, USA

DETC2006-99478

AN ENHANCED CHANGE MODES AND EFFECTS ANALYSIS (CMEA) TOOL FOR MEASURING PRODUCT FLEXIBILITY WITH APPLICATIONS TO CONSUMER PRODUCTS

Darren A. Keese
dkeese@mail.utexas.edu

Neha P. Takawale
neha.pt@mail.utexas.edu

Carolyn C. Seepersad
ccseepersad@mail.utexas.edu

Kristin L. Wood
wood@mail.utexas.edu

Department of Mechanical Engineering
The University of Texas at Austin
Austin, TX 78712

ABSTRACT

Contemporary product designers seek to create products that are not only robust for the current marketplace but also flexible for future changes, adaptations, and evolutions. This type of product flexibility is distinctive from mass customization, product architecture of singular products, and product families. The intent is to design products that intrinsically enable future changes even though such changes may not be known or planned in the current product offering. To accommodate product flexibility of this type, research advancements are needed in terms of fundamental design principles and evaluation methods for predicting and improving the flexibility of a product. This paper presents advancements in both areas. We first present the systematic enhancement of a flexibility assessment tool referred to as CMEA, Change Modes and Effects Analysis. CMEA provides the basic ability to assess the flexibility of a product, with analogous features to the well-known Failure Modes and Effects Analysis. Our enhancements extend the method to provide for intuitive and more repeatable measures of flexibility. We then use the enhanced CMEA to investigate a variety of consumer products with the goal of inductively deriving product flexibility principles. Concrete applications are shown for these principles from the domain of power yard tools, such as hedge trimmers, weed trimmers, and leaf blowers. Also, the applications are used to demonstrate the value of the CMEA enhancements.

1. INTRODUCTION

Product flexibility, defined as the ability for a product to adapt to changing or varied requirements, is a vital contributor to a product's success. For products introduced into today's competitive markets, flexibility is necessary for meeting a wide range of current and future requirements. Customer requirements change over time as technology advances, cultural trends evolve, and manufacturers expand to new markets. As technology advances, flexibility has become the primary measure of success in production, because customers are no longer satisfied with a small selection of mass-produced choices [1]. For example, Sony's success with Walkman products in the 1980's resulted from the large variety of Walkman products introduced into the marketplace, and this variety stemmed from a basic design that was flexible enough for easy adaptation into multiple products [2].

Similarly, the two chairs in Figure 1 fulfill the same product requirements, but the chair on the right is more flexible for design changes. Any change to the chair on the left requires redesign of the entire chair (because it has only one, integral part), as well as adjustments to the manufacturing chain. The modular chair on the right could incorporate new features, such as a higher backrest or armrests, without changing most of its parts.

FIGURE 1. PRODUCTS WITH INCREASING FLEXIBILITY FOR DESIGN CHANGES, FROM LEFT [3] TO RIGHT

It would be helpful for designers and manufacturers to have a tool for analyzing product designs for flexibility and to have general guidelines for designing flexibility into product architectures.

1.1 CMEA Overview

Change Modes and Effects Analysis (CMEA) [4] [5] is a tool for measuring a product's flexibility towards change and thereby diminishing the cost of redesign and shortening time-to-market. It facilitates evaluation of products for their flexibility towards adaptation, from the designer's point of view. This tool can identify weak points in a design that make it difficult and costly to change a design. CMEA also facilitates comparisons of the flexibility of different products. Accordingly, it can be used to help identify principles of design that inherently aid or hinder flexibility in a product.

The goal of CMEA is to aid designers in minimizing the costs associated with redesigning and manufacturing a product as it evolves into new iterations. CMEA therefore focuses on the aspects of a design that increase the cost and delay changing production processes to accommodate an altered form of a product. These aspects are tied closely to how much of the original product must be manufactured differently and how prepared the manufacturer is to make changes to its manufacturing chain.

CMEA has some similarities to Failure Modes and Effects Analysis (FMEA). To evaluate a product under CMEA, each of a product's potential redesign changes are evaluated for three criteria: design flexibility, readiness, and occurrence. These three ratings are evaluated in an algebraic function to produce a Change Potential Number (CPN) for each potential change. The CPN can be used to identify problem areas in a design by correlating certain design features with high CPN's. Averaging the CPN's for a product gives a general flexibility rating that can be compared across products.

Palani Rajan and coauthors [6] suggest that possible future work in the development of the CMEA method would be to use CMEA to create "generative design methods to assist product developers." They also mentioned the need for a "generic flexibility metric." We have contributed to their suggested future work by enhancing CMEA methodology and applying it to a domain of consumer products. Our enhancements to CMEA make it less subjective and more consistent when different people perform the analysis. We have also adjusted the ratings system so that ratings can be understood more intuitively and so that CMEA more closely resembles FMEA, which prevents possible confusion for those who are already familiar with FMEA. Finally, we have applied the new CMEA method to a set of consumer products in order to identify some design guidelines that enable flexibility.

1.2 Related Work

There have been previous efforts to develop methods for measuring product flexibility. Part of the reason for different methods is the lack of a single consistent definition for product flexibility. Consequently, Shewchuk [7] suggested a generic metric that would be used by a designer to develop his or her own applicable flexibility measure based on his or her own view of flexibility. CMEA, conversely, is intended to produce consistent results when used by any designer so that its results can be easily interpreted by different users. Some other measures of flexibility are based on redesign effort, time, or cost [8]. CMEA instead focuses on costs due to manufacturing changes, because these are the bulk of the costs associated with a new product.

Jiang and Allada [9] approach the issue of changing customer requirements as a robustness design problem. They have adapted the Taguchi methodology for improving robustness to this situation. Unlike CMEA, this method evaluates entire product families rather than individual products, and it focuses on product functions instead of components.

Jaikumar [10] and Das [11] look at flexibility with a focus on the manufacturing system as a whole. CMEA puts the focus on the product itself so the designer can use its results to improve the product's design for flexibility.

Martin and Ishii [12] developed an index for the cost of redesign (including design effort, tooling and testing) called the generational variety index (GVI), based on quality function deployment (QFD) with estimates for the costs and rates of change of customer requirements. This index requires knowledge of all expected changes and involves estimating the redesign costs for each engineering metric in the QFD as a percentage of total product cost. They also created a coupling index (CI) to be used with the GVI to design products with low cost of redesign. The CI measures flows of design information and energy between components. This methodology has a similar goal to that of CMEA: "to reduce the amount of redesign effort for future generations of the product." However, CMEA considers not only parametric changes, but also added functionality.

Several commonality indices have been developed to measure the degree of commonality in a family of products: Degree of Commonality Index [13], Total Constant Commonality Index [14], Product Line Commonality Index [15], Percent Commonality Index [16], the Commonality Index [17], Component Part Commonality Index [18], and the dendrogram approach [19]. Thevenot and Simpson [20] remark that commonality is measured to resolve the tradeoff between product commonality and increased manufacturing costs resulting from distinctiveness. Whereas these indices are used primarily for retrospective analysis of current or previous product families and focus only on commonality, CMEA is used to analyze a product's flexibility towards *future* changes and incorporates other aspects of flexibility such as the availability of interchangeable third-party parts and the level of readiness within the design/manufacturing enterprise for implementing changes.

Clarkson and coauthors [21] have developed the Change Prediction Method (CPM) to analyze the effect of a change propagating through coupled parts or subsystems. The CPM was presented with the goal of improving the management of redesign efforts (by identifying which changes would have high risk in terms of number of subsystems affected). Instead, CMEA's goal is a direct reduction of total effort of redesign, and therefore considers compounded severity of impact from multiple types of changes to each part. CMEA is proactive because it is used for improving the flexibility of a design instead of reacting to existing inflexibility. The CPM maps dependencies at a subsystem level. In contrast, CMEA is applied at a more detailed component level and helps identify specific design features that hinder or facilitate flexibility.

Using CMEA, it is possible to distinguish between different changes and the severity of their impact on both design and manufacturing. Accordingly, it can be used to derive actionable insights to improve the flexibility of a product. In CMEA, the effect of change propagation is evident, because increased numbers of changes results in increased redesign costs. CMEA does require the user to predict which product components will be changed by each particular future product requirement. In medium to low complexity products, this is straightforward, but a method such as CPM may make this process more manageable for high complexity products.

1.3 Research Methodology

There were two primary goals in this research. The first is to systematically enhance the CMEA flexibility assessment tool to provide measures of flexibility that are more intuitive and repeatable. The second is to use the enhanced CMEA to investigate a variety of consumer products with the goal of inductively deriving product flexibility principles.

Figure 2 shows our research approach, which is based on these goals. The research began with a brainstorming session within our research group to create a list of possible product domains that we could use as an aid while further developing CMEA and to help identify design guidelines for increased flexibility. The primary criterion was to focus on consumer products of medium complexity that would be easy to obtain, study, and understand. The product domains listed during brainstorming ranged from kitchen appliances to mechanical toys to gas-powered lawn tools. We narrowed this list of product domains to a selection of six products with the following criteria: 20-40 parts, electro-mechanical, multiple product families, multiple energy domains, and evidence of a history of redesign cycles. These criteria resulted in a group of electricity-powered lawn tool products.

We then reverse-engineered these products to gain a deeper understanding of their functions and architecture. Since the changes related to evolving products are based on customer requirements, we conducted customer interviews and researched customer reviews of the products to determine customer opinions and suggestions. This information was adapted into lists of future changes of the products to use in our research. The reverse engineering also included the subtract and operate procedure (which helped us understand the purpose of each component so we could effectively create detailed design changes) and the creation of function structures (so we could understand and characterize the complexity of the products and the layout of modules) [22]. We applied CMEA to these products for the purpose of identifying design principles related to flexibility, but discovered that the method needed some enhancements to make its results more consistent and interpretable.

We enhanced the CMEA methodology by studying the costly aspects of change and methods for objectively quantifying them. As we developed the enhanced methodology, we tested it against the products in our study and hypothetical extreme cases. We used the enhanced CMEA methodology as a tool to identify aspects of our products that aided or hindered flexibility. Then we interpreted these aspects as design guidelines for flexibility.

The next section explains the CMEA methodology along with enhancements to make application more straightforward and results more consistent. Following that section, we introduce example design principles that lead to flexible products with examples of how CMEA captures the results of employing these principles. These guidelines were derived inductively by applying the enhanced CMEA to the sample products.

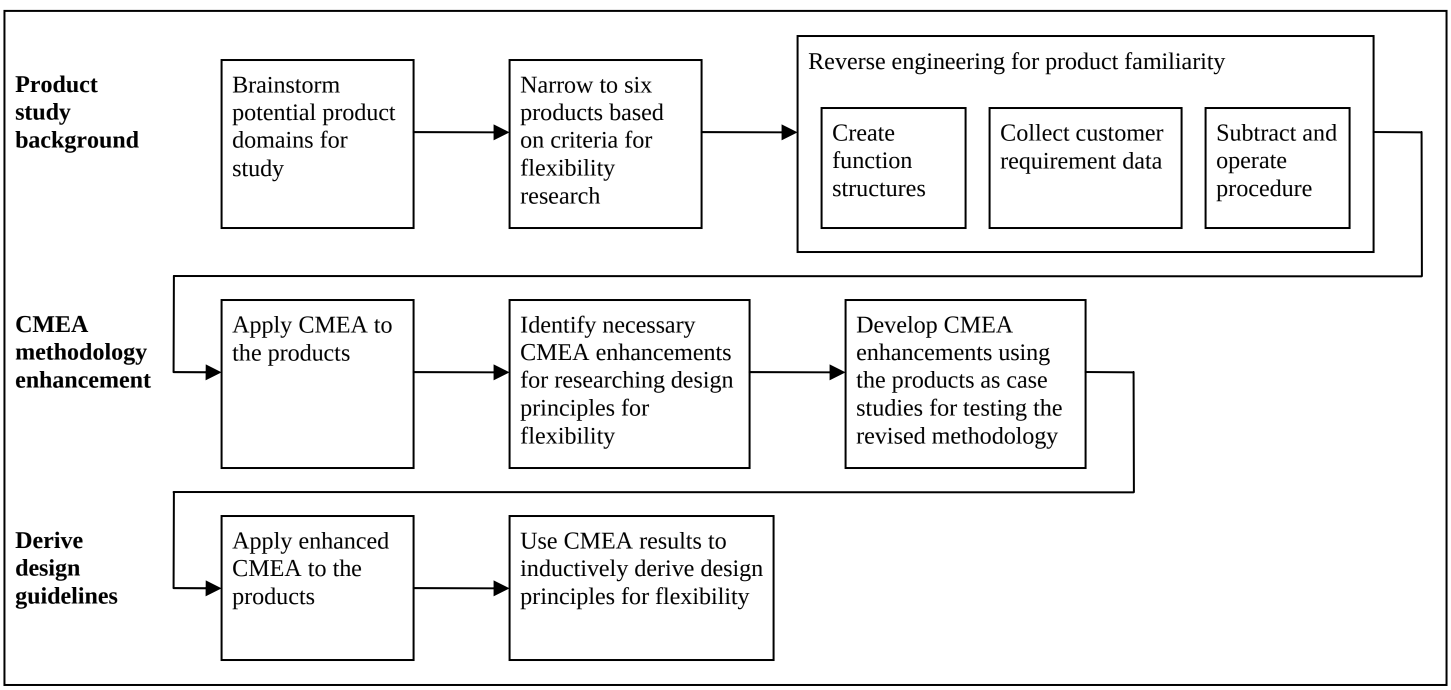

FIGURE 2. RESEARCH METHOD FLOW

2. ENHANCED CMEA METHODOLOGY

CMEA is conducted using a table that bears some resemblance to the table used for FMEA [23]. The column headings for a CMEA table are shown in Table 1. Each row of the table represents one **Potential Change Mode** for the product, and the columns are used to determine the flexibility of the product for each change mode. The gray shading indicates columns that are new to the enhanced methodology and are used to determine **Design Flexibility** more reliably than in the previous methodology. Section 2.1 explains how to perform CMEA and Section 2.2 proposes a method for creating a rubric for Design Flexibility.

2.1 Performing CMEA on a product

CMEA for a product begins with a count of the number of functions in a product by mapping its function structure. A **function** is one step in the manipulation of matter, energy or signals by the product. Many functions contribute to the overall intended function of the product. A **function structure** for a product is a flow diagram in which each node represents one of the product's functions and each flow represents matter, energy, or signals passed between functions [24]. Figure 3 is an example function structure for a Black and Decker 17" Hedge Trimmer, one of the products from the study described in Section 3.

The total number of functions is used in CMEA to normalize flexibility ratings based on the complexity of the product. For this reason, it is important that CMEA users are consistent with assigning functions to nodes. Our rule is to use a single functional node whenever multiple flows are manipulated together in the same action.

TABLE 1. COLUMNS FOR A CMEA TABLE

Affected Components	**Potential Change Mode**	**Potential Effect(s) of Change**	3rd-Party Replacement	Geometry Change	Mfg. Process Change	Material Change	Assembly Sequence	Assembly Method	**CFR**	**Design Flexibility (*F*)**	**Potential Cause(s) of Change**	**Occurrence (*O*)**	**Readiness (*R*)**	**CPN**

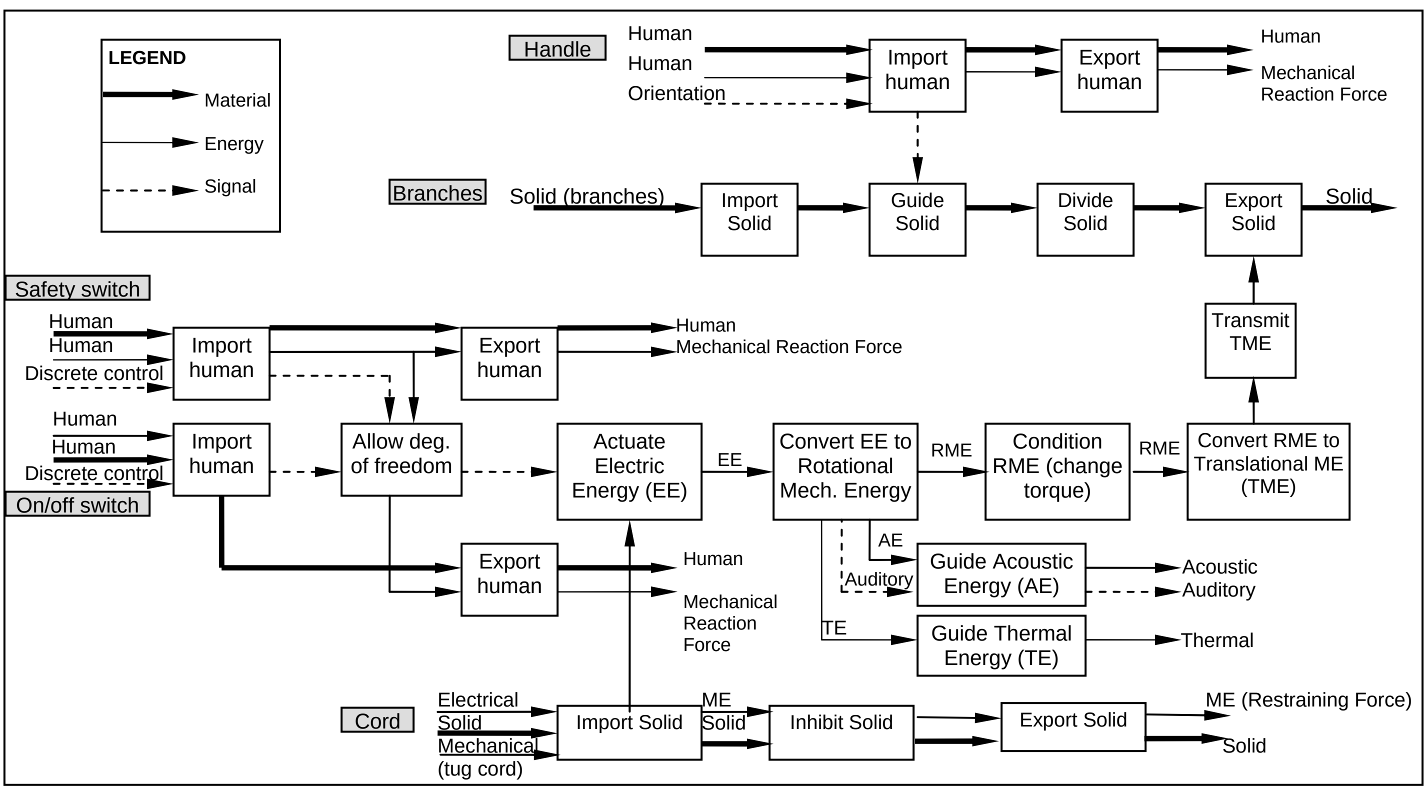

FIGURE 3. FUNCTION STRUCTURE FOR BLACK AND DECKER HEDGE TRIMMER TR1700

Next, a list of **Potential Change Modes** to the product should be compiled. The list should consist of as many potential changes as possible. This list can be interpreted from known customer requirements (both fulfilled and unfulfilled), as well as futuristic requirements created from futuristic market or innovation studies. These potential changes can be found by performing surveys and interviews, reading customer reviews of similar products, and researching competing or analogous products. To produce Potential Change Modes in our product study, we obtained a list of customer requirements from interviews and reviews, and we ran a brainstorming session for realistic methods to improve the products in terms of each requirement. These changes should be filled into the CMEA table along with their respective **Potential Cause(s) of Change**. For example, a potential change for a power tool might be "add a rubber grip to the handle" and its potential causes might be "increased user comfort" and "less likely to slip in hand."

In each row, the **Affected Components** column should list the components that will be altered or replaced. Removed components should not be counted, because the cost of their removal is contained in the alterations to neighboring parts. In our enhanced methodology, the definition of a component is important for calculating Design Flexibility (explained below). We have defined a **component** as one of the following:

- A single unit part of one material produced by the manufacturer.
- Something ordered from a third party as a unit.
- Bolt/washer/nut/fastener combinations are included together as one component, because the design and part-ordering considerations of these combinations essentially treat them as a unit.
- A circuit board is a single component.
- A set of wires in the same circuit are a single component, because all the wires in a circuit work together, sharing the same function.

Paint, labels, lubricant, and fluids do not count as components because they are trivial or difficult to count as units.

The **Potential Effect(s) of Change** column should be filled with the most likely means of implementing the change mode, explaining how each component is affected (replacement, geometry, orientation, material, function, or assembly method). In our enhanced methodology, the nature of these changes is important for determining Design Flexibility, because each type of change adds to the cost of redesigning the manufacturing of the product. The enhanced methodology does not consider added or removed components, so it does not penalize the product's flexibility rating for potential changes that are inherently complex.

Next, three ratings are found for each of the potential changes, and these are used to find a **Change Potential Number (CPN)** for each potential change. The enhanced CMEA methodology uses a different scale for the three ratings so they are easier to use and understand. Now, all three ratings (*F*, *O*, and *R*) are on scales of one to ten, and higher numbers are considered worse, matching the scales of FMEA's three categories. The ratings are defined as follows.

- **Design flexibility (*F*)** reflects how difficult and costly it is to start producing the product with the change. It represents the extent of the product that must be redesigned and manufactured differently. This rating reflects qualities of the current product design, regardless of who currently manufacturers it. A one represents a potential change that is nearly negligible in terms of cost, and a ten represents a potential change that requires complete redesign of the product.
- **Occurrence (*O*)** reflects the probability of a particular change occurring. Changes are categorized as either time-dependent (occurring multiple times over multiple redesign cycles) or opportunistic (meeting a feature opportunity or solving a drawback in the current version of the product). For a time-dependent change, a one represents a change that is extremely unlikely to be implemented over the range of time under consideration (for example, the next ten years), and a ten represents a change that is likely to occur many times in this time range. For an opportunistic change, a one represents a change that is extremely unlikely to be implemented, and a ten represents a change that will certainly be implemented in the next iteration of the product.
- **Readiness (*R*)** reflects how easily the manufacturer can begin to implement the change in its manufacturing chain. This rating reflects only qualities that are specific to the particular manufacturer of the product. It involves supply chain flexibility, organizational flexibility (company's reaction time to a change), and financial readiness to implement the change. A one represents a potential change that can be implemented immediately without cost, and a ten represents a potential change that the company can not feasibly implement.

Of these three, Design Flexibility is the one that designers can control immediately. Occurrence and Readiness indicate the proposed changes that offer maximum savings in redesign.

Our enhanced methodology improves the determination of **Design Flexibility (*F*)**. The enhanced method includes the counting of specific alterations to the current components and assembly. This enhancement creates or prescribes more consistent results between different users of CMEA, and the results are more trustworthy, because they rely on a count of each of the significant contributors to redesign cost.

The ***F*** rating is on an integer scale from 1 to 10, where 1 is ideal flexibility and 10 is complete inflexibility, based on the complexity range of products under consideration. This is reversed from the prior *F* scale. We made this change to the system so that all three ratings, ***F***, ***R***, and ***O***, are consistent and higher ratings for one means greater cause for concern for the designer. This also parallels the three ratings of FMEA, in which higher ratings also mean greater cause for concern for the designer.

The determination of ***F*** begins with finding the **Changes-to-Function Ratio (CFR)**. The manufacturer must determine its own rubric that converts the CFR into *F*. This rubric should be specific to the complexity of products the manufacturer intends to compare or produce. A methodology for determining a rubric is presented in Section 2.2. The CFR is the total number of required part/assembly changes for a change mode divided by the total number of functions in the product's function structure. The changes in the CFR indicate a total cost of change, and the number of functions indicates the complexity of the product. The CFR is effectively a cost-of-change indicator that is normalized to the complexity of the product, so that products of varying complexity can be compared.

The method for counting product changes for the **CFR** is as follows. For each of the following six categories, the number of affected components or assembly steps is counted and tallied in the table. These six categories were selected because they represent types of redesign manufacturing changes of significant and approximately equal implementation cost, and they have a cumulative effect on cost. Therefore a single component may be counted under multiple categories. Changes that occur to identical components should only be counted once, because duplicating a change on identical components does not result in cumulative costs.

1. **Third party replacement—**Count the number of third-party components that are exchanged for alternate third-party components. For example, changing the power of a motor requires a motor replacement, or changing strength requirements of a product may require a set of fasteners to be replaced with stronger fasteners.
2. **Geometry change—**Count the number of non-third-party components that undergo changes in geometry. The nature of the geometry change is not necessary to consider, because the bulk of the cost is in updating the way it is manufactured, not in design effort.
3. **Manufacturing process change**—Count the number of non-third-party components that must be manufactured under a different process. An example would be a metal part that was previously stamped but now requires laser cutting.
4. **Material change**—Count the number of non-third-party components that are made from a different material.
5. **Assembly sequence reordering**—Count the number of steps in the assembly process that have been reordered. Do not count steps that have been delayed because of inserted steps, or steps that have been pushed up because of removed steps. (Only reordered steps are significant enough to count.)
6. **Assembly method change**—Count the number of *modules* that must be attached differently. Examples are modules that use different types of fasteners or attach in a different orientation or location. In this case, modules are counted rather than components so that multi-component modules that are attached as a unit do not inflate the score.

Added and removed components are not counted because that would cause CMEA to penalize scores based on the complexity of a change rather than the current product's flexibility towards the change.

Occurrence (*O*) should be calculated based on the manufacturer's economic strategy and known customer requirements obtained from market projections, customer surveys, interviews, sales records, etc. There are two categories of change modes which must be evaluated differently for *O*:

1. Opportunistic changes—These changes involve features that solve drawbacks or fill new opportunities in the current product. The *O* rating should indicate the likelihood of the change for the current product. Example: Add a bubble level to a hand drill.
2. Time-dependent changes—These changes may occur repeated times over several redesign cycles because they are related to changing technologies, customer needs, or economic goals. The *O* rating should indicate how many times the change is likely to occur over multiple redesign cycles for the period of time under consideration by the designer. Example: Change motor power.

Opportunistic change *O* ratings can be based on how many times the drawback or opportunity appears in customer reviews and interviews, where a 1 is a change that customers do not care about, and a 10 is a change that customers demand. This mapping will depend on the customer data available to the designer.

Time-dependent change *O* ratings should be determined based on a rubric that considers how likely and how often a change mode will occur over a period of time the CMEA user wants to consider. Palani Rajan [23] provided the metric in Table 2 as a generic rubric for time-dependent changes, and we have used this rubric in our study in Section 3. It considers how many times a change will occur in the next ten years of redesigning a product.

TABLE 2. A GENERIC METRIC FOR DETERMINING OCCURRENCE (O) FOR TIME-DEPENDENT CHANGES [23]

Probability of Occurrence	No. of times in next 10 years	Ranking (*O*)
Very high and is almost inevitable	10-9	10-9
High: Repeated occurrence	8-7	8-7
Moderate: Occasional occurrence	6-5	6-5
Low: Relatively few occurrences	3-4	3-4
Remote: Unlikely to occur	2-1	2-1

Readiness (*R*) for a particular potential change should be determined by a study of the manufacturer's ability to accommodate the change in terms of manufacturing readiness, supply chain readiness, organizational readiness, and financial readiness. This internal corporate information is not readily available to those outside a company. Therefore, each manufacturer must create their own rubric for *R*, based on these contributing factors. In the absence of this internal information, we have chosen to omit *R* from our consumer product study.

The **CPN** for a potential change is the product of *F*, *O*, and *R*. This method of calculating CPN is greatly simplified from the previous CMEA formula, and is made possible by our changes to the scales for the three ratings. This simplified formula also parallels the formula for the RPN in FMEA, which increases the intuitiveness of CMEA for those already familiar with FMEA.

The primary goals in our work were to simplify the method so it is more intuitive to understand, and to create a method for finding the Design Flexibility (*F*) for each particular change such that subjectivity is removed, producing more consistent and trustworthy results. We have not expanded on the methods for finding the other two ratings, Occurrence (*O*) and Readiness (*R*). The new metric for measuring *F* is less subjective and more consistent because it relies less on intuition, while still capturing the necessary aspects of design flexibility.

The following is a summary of the procedure for performing CMEA:

1. Create a function structure for the product and count the total number of functions.
2. Enter as many Potential Change Modes as possible in the CMEA table.
3. Record Potential Causes of each change mode in the CMEA table.
4. For each change mode, enter Affected Components in the CMEA table and describe the nature of how they are affected in the Potential Effect(s) of Change column.
5. For each change mode, count the number of resulting changes in the six categories of the CMEA table.
6. For each change mode, calculate the Change-to-Function Ratio (CFR) by dividing the total number of changes by the number of functions in the product.
7. For each change mode, use a rubric to determine *F* from the CFR.
8. For each change mode, use a rubric to determine *O* from the Potential Cause(s) of Change.
9. For each change mode, use a rubric based on internal manufacturer data to determine *R*.
10. Calculate the Change Potential Number for each change mode by multiplying *F*, *O*, and *R*.

2.2 Proposed Method for Creating a Design Flexibility (*F*) Rubric

The purpose of a quantitative rubric for *F* is to define its 1-10 scale, such that the CMEA user can easily identify designs with “good” or “poor” flexibility. For this reason, a rubric that maps the CFR to *F* should be based on the range of design flexibility that the CMEA user expects to encounter. Then the CMEA user will have an intuitive understanding of how to interpret an *F* rating.

We propose creating a rubric based on an analysis of a product that the designer considers to have very poor flexibility. This product will be used to define the upper bound of flexibility (worst possible flexibility), based on the range of products with which the particular designer, design group, or manufacturer is familiar. To begin, a product with very poor flexibility (according to the designer or design group) is selected. Then CMEA is performed on it as described in the previous section, to the point of assigning CFR’s to all potential change modes. The maximum CFR corresponds to the worst possible flexibility, an *F* of 10. An *F* of 1 represents ideal flexibility, which occurs when a change mode requires no redesign cost. Therefore, a CFR of 0 should result in an *F* of 1. A linear interpolation is used to assign ranges of CFR to each integer value of *F* from 1 to 10. This results in the following formula for *F*.

$$F = \mathrm{int}\left[\frac{9 \cdot CFR}{CFR_{\max}} + 1\right] \tag{1}$$

For example, in our product study, CFR_{max} was 0.286. Among our products, a *CFR* of 0 results in the following.

$$F = \mathrm{int}\left[\frac{9 \cdot 0}{0.286} + 1\right] = 1 \tag{2}$$

A CFR of 0.286 results in the following.

$$F = \mathrm{int}\left[\frac{9 \cdot 0.286}{0.286} + 1\right] = 10 \tag{3}$$

A CFR of 0.147 results in the following.

$$F = \mathrm{int}\left[\frac{9 \cdot 0.147}{0.286} + 1\right] = \mathrm{int}[5.63] = 6 \tag{4}$$

When the rubric is used, it is possible for the user to encounter CFR’s above the original range. These can be bounded to *F*’s of 10, but they indicate that the expected range of flexibility has expanded, so the designer should consider readapting the rubric for future use.

3. APPLYING THE ENHANCED CMEA METHOD TO A SET OF PRODUCTS

We applied the enhanced CMEA to a set of six consumer products. The application facilitated identification of design principles that enable flexibility and enhancement of the calculation of Design Flexibility (*F*) for CMEA. To identify design principles for flexibility, we studied characteristics of the products that correlated with high or low *F* ratings for particular change modes to identify design characteristics that correspond to improved or worsened flexibility. We also searched for commonality between products with high or low overall flexibility ratings.

The following are the criteria we used to select the six products for the study, and the reasoning behind our choices. All of the products are from the consumer product domain, because consumer products have more frequent redesign cycles and larger customer bases. These features made it easier to produce customer requirement lists. The products all have between 20 and 40 parts. Accordingly, they are complex enough to demonstrate many principles of flexibility but simple enough to understand thoroughly. Some of the products share similar basic functionality while others exhibit very different functionality. This feature provides opportunities for comparisons of different solutions to similar problems and comparisons of flexibility between products that solve different problems. Most of the products are Black and Decker brand, which is known in the industry for flexible products [25]; therefore, it is highly likely that several principles of flexibility are represented in the products. One of the products represents a different brand (Toro), which may exhibit different levels of flexibility compared with the Black and Decker products.

The six products in the study were a Black and Decker 17” Hedge Trimmer, a Black and Decker HedgeHog XR Pivoting Head Hedge Trimmer, a Black and Decker Cordless Shrubber, a Black and Decker Grass Hog String Trimmer, a Black and Decker Blower/Vac, and a Toro Leaf Blower. Table 3 is an excerpt from CMEA for one of the products, the 17” hedge trimmer shown in Figure 4. For the complete CMEA, see the Appendix. Readiness (*R*) was omitted in this study because of a lack of internal manufacturer information.

FIGURE 4. BLACK AND DECKER 17” HEDGE TRIMMER FROM THE PRODUCT STUDY

This section highlights the design principles for flexibility we have found in this study with explanations of how CMEA captures this flexibility. The list of principles is not intended to be exhaustive, but it is representative of the types of principles that can be uncovered with a thoughtful implementation of CMEA.

Many of these design principles are a tradeoff for flexibility at the expense of some other design goal. In these cases, the designer must determine the appropriate tradeoff between flexibility and other, conflicting design goals.

1. Confine functions to single modules.

Newcomb, et al. [26] note that “modularity is the concept of separating a system into independent parts or modules which can be treated as logical units.” It is widely accepted that careful use of modules can increase flexibility. For future-change flexibility, this is achieved by placing functions in separate modules, so the interfaces between modules are not meshed. When a function is stretched between two modules, a change to either module is likely to affect both, resulting in greater cost. Essentially, cross-module functions are bridges for change propagation.

In the cordless shrubber product (Figures 5 and 6), the function of containing the gears is shared by the lower blade and by the gear housing. There are several ways the blades may be changed that would require a change to the gear housing and outer casing to accommodate the need to contain the gears. The extra cost would be reflected in CMEA. For change modes involving the blade module, the parts of the gear assembly would also contribute to the count of changes, resulting in a higher CFR and *F*.

TABLE 3. PART OF THE CMEA FOR THE BLACK AND DECKER 17” HEDGE TRIMMER

Affected Components	**Potential Change Mode**	**Potential Effect(s) of Change**	3rd-Party Replacement	Geometry Change	Mfg. Process Change	Material Change	Assembly Sequence	Assembly Method	**CFR**	**Design Flexibility (*F*)**	**Potential Cause(s) of Change**	**Occurrence (*O*)**	**Readiness (*R*)**	**CPN**
left casing half; right casing half; motor; large gear; small gear	Scale motor up or down	The casing must be scaled to accommodate the space for the new motor and provide suitable mounting for it. The gears should be re-optimized for the new torque.	3	2	-	-	-	-	0.238	8	Cost; power; weight; product life; noise level	4	-	32
left casing half; right casing half; safety switch	Remove safety switch without removing auto-locking feature	The switch interface needs a new mechanism so it can still lock. The safety switch is removed and the gap in the casing must be covered.	-	3	-	-	-	-	0.143	6	Cost; ease of use	3	-	18
left casing half; right casing half; safety switch	Add second required switch to secondary handle	The secondary handle must provide mounting for the switch and circuit switch. The casing must allow for wire to pass from it to the secondary handle.	-	3	-	-	1	1	0.238	8	Reduce accidental starts and possible hand injury	1	-	8
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…

FIGURE 5. BOTTOM VIEW OF THE CORDLESS SHRUBBER

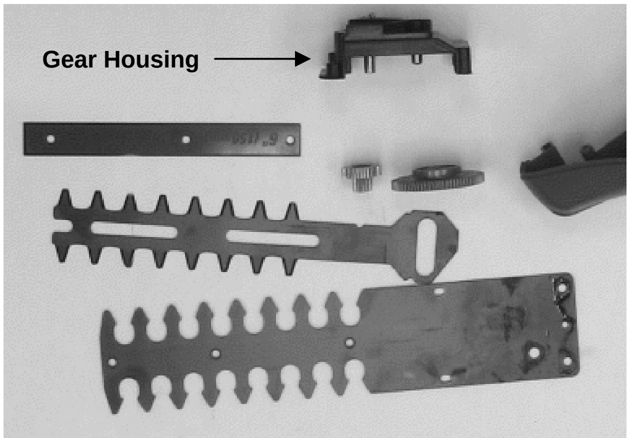

FIGURE 6. EXPLODED VIEW OF THE BLADE AND GEAR HOUSING MODULES

2. Confine functions to as few components as possible.

If a single function is performed by multiple components, then a change to that function affects all of those components, resulting in increased cost. In CMEA, this appears as a greater number of components counted towards the CFR and *F*. An example of a function accomplished by multiple components is a gear train. All the gears in the train work together to perform the same function of scaling torque. A change to the gear train is likely to affect all gears; therefore, using fewer gears in the train increases flexibility. In this case, there is a tradeoff between increasing flexibility by reducing the number of gears, and saving space by effectively using multiple gears.

3. Use a framework for mounting multiple modules.

A framework reduces the number of interfaces between modules and therefore prevents them from affecting each other when some of them are changed. If multiple components or modules are altered such that their interfaces must change, all the interface changes can be absorbed by the framework. As a result, fewer components will be affected by interface changes. This would result in a lower count of changes in CMEA's CFR and *F*.

The casing shell of the blower/vacuum in Figure 7 is an example of the use of a framework for increased flexibility. The casing provides mounting for almost all the modules in the product. Three of these modules are marked in the figure. Each can be manipulated independently by a designer because they do not interface with each other.

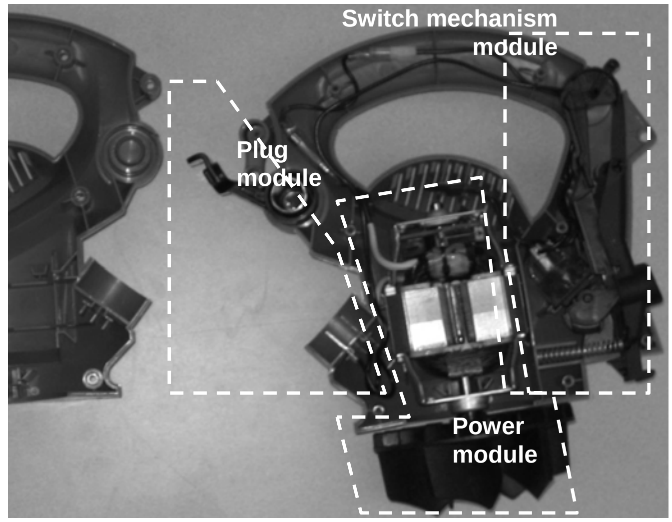

FIGURE 7. INTERIOR VIEW OFBLOWER/VACUUM WITH MODULES MARKED

4. Preserve space for changes in geometry, orientation, and location of modules.

If a change to a part's geometry, orientation, or location forces other parts to change to accommodate it, then those parts are dependent on it. An example would be tightly arranged components that must all be rearranged if one of them is enlarged. Fewer of these dependencies results in fewer components affected unnecessarily by product changes.

The cordless shrubber in Figures 8 and 9 has a missed opportunity for preserving space to increase flexibility. As marked in Figure 9, the area to the left of the batteries could be extended. This extension could provide the option of increasing the number of battery cells (or adding some other component) without altering any current components. Without this extension, the casing halves must be altered if battery cells are added.

FIGURE 8. EXTERIOR OF THE CORDLESS SHRUBBER

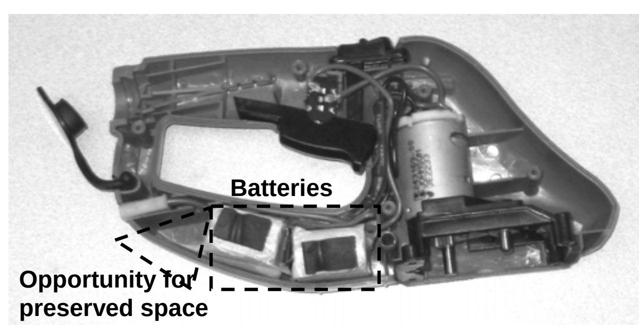

FIGURE 9. INTERIOR VIEW OF THE CORDLESS SHRUBBER

5. Provide free interfaces.

When new features are added to a product, they usually require a means of interfacing with existing parts. A free interface is a location where a new component or module can be attached without any changes to the currently existing parts.

The string trimmer in Figures 10 and 11 has a free interface. New modules can be attached to the pole in the same way as the current secondary handle: a tightened U-bracket. Modules added in this manner result in no redesign cost. In CMEA, they will have CFR's of 0, resulting in ideal Design Flexibility.

There is an additional opportunity for a free interface on the string trimmer. One change mode we considered in our CMEA was to add some slots on the exterior of the product to store extra spools in. This could be added on the long, flat area in front of the switch at relatively low cost, because this free area follows principle 4 from above. Flexibility would be further improved by adding snap-fit slots or increasing the curvature of this area, resulting in a free interface for attaching the new spool storage module.

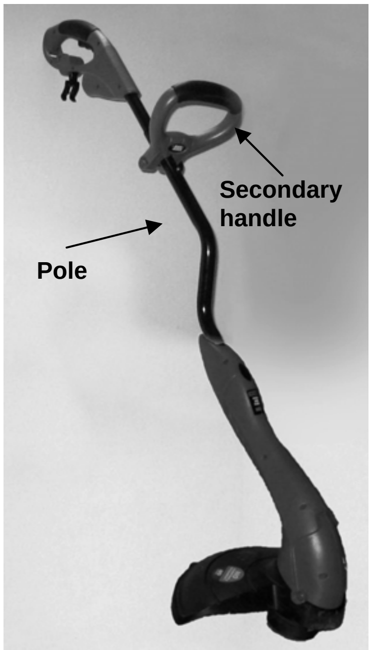

FIGURE 10. STRING TRIMMER FROM THE PRODUCT STUDY

FIGURE 11. CLOSE VIEW OF STRING TRIMMER

6. Implement as many identical parts as possible, without raising the parts count.

Often, identical parts can be changed together so they can continue to be mass produced together. This results in fewer unique product changes (a lower CFR and *F* in CMEA) which lowers the cost of redesign.

The 17" hedge trimmer from the product study (pictured in Figure 4) could benefit from the use of this principle. One change mode considered in the CMEA was to reduce vibration by altering the mechanism to make both blades move. (One of the blades is currently stationary.) Currently, the two blades have different geometry, as illustrated in Figure 12. After the change, they would be identical. The two blades could have been identical in the original product. With careful design, both necessary types of interfaces for the moving and the stationary blades could have been incorporated into a single component geometry. Since CMEA counts identical parts as single components, the benefit would appear in the analysis as one less geometry change.

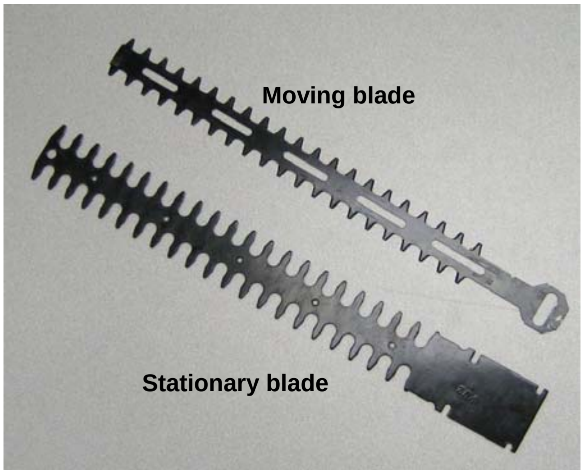

FIGURE 12. BLADES FROM THE 17" HEDGE TRIMMER

7. Design modules to assemble along the same direction.

It is easier to make changes to parts without affecting the assembly process if all parts assemble in the same direction. If the product assembly requires some parts to be attached in different directions, it is more likely that changes to some of those parts may require an altered assembly process. CMEA captures this aspect of flexibility by recording the number of assembly steps that have been reordered (sequence changes) and steps that are performed in a different manner than before (method changes). If a component's geometry changes, but it is still attached in the same manner, in the same direction, and does not alter the assembly of other components, then it does not contribute to the assembly tallies.

This design principle is also a well-known guideline for Design for Assembly: Insert parts from the same direction or very few directions [27] [24]. It is serendipitous that this principle is beneficial for both types of design goals.

The flexibility of the pivoting head hedge trimmer (Figures 13 and 14) fails to follow this principle. This hedge trimmer has a pivoting handle that can provide extra blade reach but also makes the product more cumbersome. A change mode considered in CMEA was to remove the pivot feature to

FIGURE 13. PIVOTING HEAD HEDGE TRIMMER FROM THE PRODUCT STUDY

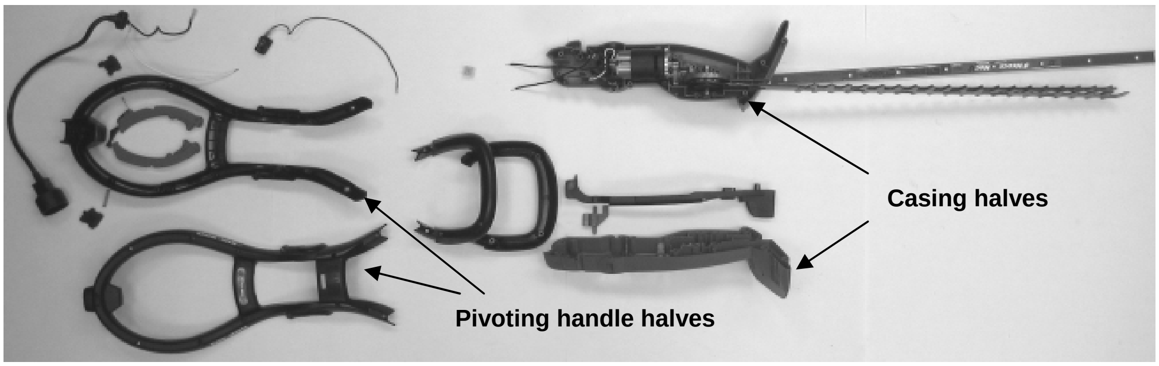

FIGURE 14. EXPLODED VIEW OF THE PIVOTING HEAD HEDGE TRIMMER

decrease manufacturing and retail cost and to improve ease of use. To accommodate this change, the handle section is removed, and the components mounted in it (plug, switches, and safety switches) are incorporated into the main casing section. The main casing section is split horizontally while the handle section is split vertically. As a result, the switches, which pivot normal to the split, must be redesigned to be mounted along a different axis. Additionally, the assembly process must be updated because the switches and plug must be inserted in a different direction. All of these changes contribute to a higher *F* rating in CMEA. If the pivoting handle had been split vertically in the original product to match the split in the rest of the product's body, many of the components and assembly steps could have remained unchanged.

<u>8. Provide the capability for excess energy.</u>

If a product has the means to use more energy than necessary to complete its functions, then there is energy available for new functions that are added to the product in future redesign cycles, without the need to change power sources and/or power manipulation components. In a product family, this same principle allows products with different energy requirements to use more common components. This principle does not necessarily imply that the product must waste energy.

There are means of providing excess energy that will only be used when required. For example, in a rechargeable battery-operated product, providing a battery with excess capacity will not waste energy, but instead result in less frequent charging. As a positive side effect, an increase in required energy may not require a new battery in order to maintain adequate time per charge. Another example would be the use of a variable-torque motor with electronically-controlled torque. Changing the torque requirements would not require a new motor with new mounting. In CMEA, this would result in fewer changes counted towards the CFR and *F*.

4. CONCLUSIONS AND FUTURE WORK

We have presented an enhanced methodology for Change Modes and Effects Analysis with improved repeatability and interpretability. It is more repeatable because it uses an improved rubric for measuring design flexibility that does not involve estimation. It is easier to interpret because the ratings now have matching scales and are analogous to the established FMEA ratings.

We have applied CMEA to a group of products and used the results to produce the following design guidelines for increasing product flexibility:

1. Confine functions to single modules.
2. Confine functions to as few components as possible.
3. Use a framework for mounting multiple modules.
4. Preserve space for changes in geometry, orientation, and location of modules.
5. Provide free interfaces.
6. Implement as many identical parts as possible, without raising the parts count.
7. Design modules to assemble along the same direction.
8. Provide the capability for excess energy.

This list of guidelines is not exhaustive, and we expect to expand it as we study additional products. Also, it could be beneficial to identify guidelines for designing product families, since CMEA is currently intended for single evolving products. We would also like to compare our guidelines with those discovered by other means, such as metrics for redesign cost or studies of existing products and patents. Also, future work should focus on improved determination of Readiness ratings. Readiness should be based on several factors and probably requires a rubric to combine them into a single rating.

When the list of change modes for CMEA is produced, it includes only the set of future changes that can be predicted. Especially for long term changes, it is impossible to accurately predict all possibilities for a changing market with changing technology. We hypothesize that flexibility towards short-term changes indicates flexibility to changes in general, and therefore the omission of some potential changes does not significantly affect the usefulness of CMEA. It may be true that design guidelines that enable flexibility will be universally useful, so that attempts to predict long-term changes become unnecessary. More investigation is needed.

Finally, it would be challenging to apply CMEA to high complexity products. The effort of applying CMEA is likely to increase exponentially as product complexity increases because of increased interdependency between subsystems. One method of reducing analysis effort for complex products could be to subdivide the product into subsystems and to analyze each separately. In such a case, the use of Clarkson and coauthors' Change Prediction Method [21] could be helpful for identifying subsystems of interest and appropriately dividing the product into subsystems without omitting possible component changes. Also in future work, it would be desirable to apply the Change Prediction Method and CMEA on the same products for a comparison of the results. Although the approaches and goals of these two tools differ, they are similar enough that a comparison could provide valuable insights into each.

REFERENCES

[1] Olewnik, A., Brauen, T., Ferguson, S. and Lewis, K., 2004, "A Framework for Flexible Systems and Its Implementation in Multiattribute Decision Making," *Journal of Mechanical Design*, 126(3), pp. 412-419.

[2] Sanderson, S. and Uzumeri, M., 1995, "Managing Product Families: The Case of the Sony Walkman," *Research Policy*, 24(5), pp. 761-782.

[3] Twentytwentyone, "Panton Stacking Chair", http://www.twentytwentyone.com/displayProduct.asp?ProductID=59&oldreferrer=#. Accessed: May 17, 2006.

[4] Palani Rajan, P. K., Wie, M. V., Campbell, M., Otto, K. and Wood, K., 2003, "Design for Flexibility - Measures and Guidelines," *International Conference On Engineering Design*, Stockholm, Sweden, ICED.

[5] Palani Rajan, P. K., Van Wie, M., Campbell, M. I., Wood, K. L. and Otto, K. N., 2005, "An Empirical Foundation for Product Flexibility," *Design Studies*, 26(4), pp. 405-438.

[6] Palani Rajan, P. K., Wie, M. V., Campbell, M., Otto, K. and Wood, K., 2004, "Empirical Study on Product Flexibility," *Proceedings of the ASME Design Engineering Technical Conference*, Salt Lake City, UT, ASME Paper No. DETC 2004-57253, DTM.

[7] Shewchuk, J., 1999, "A Set of Generic Flexibility Measures for Manufacturing Applications," *International Journal of Production Research*, 37(13), pp. 3017-3042.

[8] Sethi, A. K. and Sethi, S. P., 1990, "Flexibility in Manufacturing: A Survey," *International Journal of Flexible Manufacturing Systems*, 2(4), pp. 289-328.

[9] Jiang, L. and Allada, V., 2001, "Design for Robustness of Modular Product Families for Current and Future Markets," *Proceedings of the ASME Design Engineering Technical Conference*, Pittsburgh, PA, ASME Paper No. DETC2001/DFM-21177.

[10] Jaikumar, R., 2001, "Postindustrial Manufacturing," *Harvard Business Review*, 64(6), pp. 69-76.

[11] Das, S., 1996, "The Measurement of Flexibility in Manufacturing Systems," *The International Journal of Flexible Manufacturing Systems*, 8(1), pp. 67-93.

[12] Martin, M. V. and Ishii, K., 2002, "Design for Variety: Developing Standardized and Modularized Product Platform Architectures," *Research in Engineering Design*, 13(4), pp. 213-235.

[13] Collier, D. A., 1981, "The Measurement and Operating Benefits of Component Part Commonality," *Decision Sciences*, 12(1), pp. 85-96.

[14] Wacker, J. G. and Trelevan, T., 1986, "Component Part Standardization: An Analysis of Commonality Sources and Indices," *Journal of Operations Management*, 6(2), pp. 219-244.

[15] Kota, S., Sethuraman, K. and Miller, R., 2000, "A Metric for Evaluating Design Commonality in Product Families," *Journal of Mechanical Design*, 122(4), pp. 403-410.

[16] Siddique, Z., Rosen, D. W. and Wang, N., 1999, "On the Applicability of Product Variety Design Concepts to Automotive Platform Commonality," *ASME Design Theory and Methodology*, New York, NY, ASME Paper No. DETC99/DTM-8762.

[17] Martin, M. V. and Ishii, K., 1997, "Design for Variety: Development of Complexity Indices and Design Charts," *Advances in Design Automation*, Sacramento, CA, ASME Paper No. DETC97/DFM-4359.

[18] Jiao, J. and Tseng, M. M., 2000, "Understanding Product Family for Mass Customization by Developing Commonality Indices," *Journal of Engineering Design*, 11(3), pp. 225-243.

[19] Hölttä-Otto, K., 2005, "Analyzing Module Commonality for Platform Design in Functional and Physical Domain," *Proceedings of the ASME Design Engineering Technical*

Conference, Long Beach, CA, ASME Paper No. DETC2005-84801.

[20] Thevenot, H. J. and Simpson, T. W., 2004, "A Comparison of Commonality Indices for Product Family Design," *Proceedings of the ASME Design Engineering Technical Conference*, Salt Lake City, UT, ASME Paper No. DETC2004-DAC57149.

[21] Clarkson, P. J., Simons, C. and Eckert, C., 2004, "Predicting Change Propagation in Complex Design," *Journal of Mechanical Design*, 126(5), pp. 788-797.

[22] Otto, K. and Wood, K., 1998, "Product Evolution: A Reverse Engineering and Redesign Methodology," *Research in Engineering Design*, 10(4), pp. 224-243.

[23] Palani Rajan, P. K., 2003, "Design for Flexibility - Measures and Guidelines," M.S. Thesis, Mechanical Engineering Department, The University of Texas at Austin, Austin, TX.

[24] Otto, K. and Wood, K., 2001, *Product Design*, Prentice Hall, Upper Saddle River, NJ.

[25] Meyer, M. H. and Lehnerd, A. P., 1997, *The Power of Product Platforms*, The Free Press, New York, NY.

[26] Newcomb, P. J., Bras, B. and Rosen, D. W., 1998, "Implications of Modularity on Product Design for the Life Cycle," *Journal of Mechanical Design*, 120(3), pp. 483-491.

[27] Tipping, W., 1965, "Component and Product Design for Mechanized Assembly," *Assembly Fastening and Joining, A PERA Conference and Exhibition*, Production Engineering Research Association of Great Britain.

APPENDIX

CMEA TABLE FOR THE 17" HEDGE TRIMMER

Change Modes and Effects Analysis Black and Decker 17" Hedge Trimmer 21 Functions															
Affected Components	**Potential Change Mode**	**Potential Effect(s) of Change**	3rd-Party Replacement	Geometry Change	Mfg. Process Change	Material Change	Assembly Sequence	Assembly Method	**CFR**	**Design Flexibility (*F*)**	**Potential Cause(s) of Change**	**Occurrence (*O*)**	**Readiness (*R*)**	**CPN**
-	Change plastic color	No functional or shape change	-	-	-	-	-	-	0	1	Aesthetics	2	-	2
-	Add a plastic blade sheath	None	-	-	-	-	-	-	0	1	Blade covered for storage and transportation	4	-	4
Stationary blade; moving blade	Change blade shape to facilitate sharpening	Redesign shape of blade edges to allow file to fit.	-	2	-	-	-	-	0.095	4	Easier for user to sharpen blades	3	-	12
-	Add liquid bath for blades	None	-	-	-	-	-	-	0	1	Keep blades sharp	2	-	2
Left casing half, right casing half, safety switch, electrical switch	Change pressure on/off switch into flip switch	The casing must seal the gap from the removed pressure switch and provide a new gap and mounting for changed parts. Safety switch is altered to work with the flip switch.	1	3	-	-	-	-	0.19	7	Easier to lock on	5	-	35
Left casing half, right casing half, safety switch, switch spring, stationary blade, moving blade	Add an auto-brake	New brake mechanism is connected to the safety switch interface and mounted into redesigned casing. Spring is swapped for a stronger spring and blades are lengthened to provide a location for the brakes to contact.	1	5	-	-	-	-	0.286	10	Blades stop quickly	3	-	30
Primary switch	Remove auto-lock feature	Change the primary switch and safety switch to prevent it from auto-locking with the safety switch.	-	1	-	-	-	-	0.048	2	Remove danger of auto-locking	2	-	4
Left casing half, right casing half	Add rubber grips to handles	Handle area of casing and secondary handle are altered to accept an adhesive rubber grip.	-	3	-	-	-	-	0.143	5	Comfortable to hold	4	-	16
Stationary blade; moving blade	Change blade length	Duplicate the designed shape of the blade edges so they are longer, or remove some to shorten.	-	2	-	-	-	-	0.095	4	Compact; wider cutting area; weight; cost	5	-	20

Change Modes and Effects Analysis Black and Decker 17" Hedge Trimmer 21 Functions															
Affected Components	**Potential Change Mode**	**Potential Effect(s) of Change**	3rd-Party Replacement	Geometry Change	Mfg. Process Change	Material Change	Assembly Sequence	Assembly Method	**CFR**	**Design Flexibility (*F*)**	**Potential Cause(s) of Change**	**Occurrence (*O*)**	**Readiness (*R*)**	**CPN**
Left casing half, right casing half	Add rigid cord guide	This guide can be an extension of the casing or a new part that affixes to the casing. Either way: a location for the cord guide is chosen to match up with plug. The casing must support the weight of the guide.	-	2	-	-	-	-	0.095	4	Cord does not get in way	7	-	28
Left casing half, right casing half	Add snap-in pole extension interface	The casing must provide an interface for the pole which allows it to snap in. The casing must also provide mounting for new circuit leads that connect with leads in the pole, so the pole has its own switch.	-	2	-	-	-	-	0.095	4	Longer reach	1	-	4
Left casing half, right casing half, stationary blade, moving blade, large gear	Dual motion blades	The ends of both blades are changed. The large gear is changed to have a new mechanism to control both blades. The casing's mounting for the bottom blade must be altered.	1	4	-	-	-	1	0.286	10	Reduced vibration	8	-	80
Left casing half; right casing half; motor; large gear; small gear	Scale motor	The casing must be scaled to accommodate the space for the new motor and provide suitable mounting for it. The gears should be re-optimized for the new torque.	3	2	-	-	-	-	0.238	8	Cost, power, weight, long life, quiet	4	-	32
Left casing half; right casing half; safety switch	Remove safety switch without removing auto-locking feature	The switch interface needs a new mechanism so it can still lock. The safety switch is removed and the gap in the casing must be covered.	-	3	-	-	-	-	0.143	5	Cost; ease of use	3	-	15
Left casing half; right casing half; secondary handle	Add second required switch to secondary handle	The secondary handle must provide mounting for the switch and circuit switch. The casing must allow for wire to pass from it to the secondary handle.	-	3	-	-	1	1	0.238	8	Reduce accidental starts and possible hand injury	1	-	8

Change Modes and Effects Analysis Black and Decker 17" Hedge Trimmer 21 Functions															
Affected Components	**Potential Change Mode**	**Potential Effect(s) of Change**	3rd-Party Replacement	Geometry Change	Mfg. Process Change	Material Change	Assembly Sequence	Assembly Method	**CFR**	**Design Flexibility (*F*)**	**Potential Cause(s) of Change**	**Occurrence (*O*)**	**Readiness (*R*)**	**CPN**
Left casing half; right casing half; secondary handle	Remove hand shield and add second required switch to secondary handle	Same as previous step, plus the gap left from removing the shield should be covered.	-	3	-	-	1	1	0.238	8	Cost; weight; compact (this part not necessary if a secondary switch is added)	8	-	64
Left casing half, right casing half	Pivoting head	The handles and switches must be redesigned into a new pivot module. The casing must accommodate the new pivot module and provide a lock and release and a rotational mounting.	-	2	-	-	2	-	0.19	7	Long reach	6	-	42