Product flexibility measurement with enhanced change modes and effects analysis (CMEA)

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Product designers seek to create products that are not only robust for the current marketplace but also flexible for future changes that may be unanticipated or unplanned. Very few techniques exist for understanding and assessing the flexibility of products for future change. In this paper, enhancements are presented for Change Modes and Effects Analysis, a flexibility assessment tool that aids designers in meeting this goal. CMEA has been systematically enhanced to improve its ease of use and increase the consistency of its application for comparing or improving product flexibility. An example application of CMEA to an existing product, a consumer power gardening tool, is provided. This application demonstrates the potential usefulness of CMEA while highlighting the improved features of the technique.

Keywords: product design, design tools, product flexibility

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1. Introduction

Product flexibility is defined as the ability to adapt a product to changing or varied requirements. For products introduced into today's competitive markets, flexibility is necessary for meeting customer requirements that change rapidly with advancing technology, evolving cultural trends, and expanding markets [1]. To meet these changing requirements, companies have adopted several types of product flexibility. Examples include product platforms for satisfying a predetermined variety of market segments with a common core of components, technologies, or manufacturing processes (cf. [2] for a review) and mass customization for late-point differentiation of products in response to customer requests (cf. [3] for an introduction). In this paper, the focus is on product flexibility for future evolution. Whereas much of the previous research on product platforms and mass customization has focused on accommodating a set of predetermined product offerings, *product flexibility for future evolution* is defined as the ability to quickly and inexpensively redesign a product into a subsequent product offering, even if the precise form of required changes is unanticipated during the design of the original product.

The three products illustrated in Figure 1 are examples of products that are flexible for future evolution. The foldable chair on the top illustrates the direct evolution of a standard, single-person chair to a reclining chair and then to a dual-person chair. The modular, accessible architecture of the original chair enables this evolution. The product in the middle is a support structure for a commercial vehicle. Extra fastener holes (23 and 24) are included in the structure to allow vehicle components to be arranged in a variety of ways to achieve a range of road clearances. The fuel cell generator on the bottom embodies several features that make it flexible for adaptation to varying power output requirements or fuel cell stack technologies [4]. Hydrogen tanks are segmented into multiple smaller tanks for easy scaling; similarly, the modular fuel cell stack can be scaled along with the attached manifold that ducts the system. Empty space within the framework enables scaling. Components are easily reconfigurable because they are fixed to a breadboard base plate and connected to each other only by hoses or wires (not pictured for clarity). All of these flexible products accommodate added features and functionality with little or no change to the original product architecture.

[INSERT FIGURE 1.]

To facilitate the design of products with flexibility for future evolution, evaluation methods and tools are needed for predicting and improving flexibility. In this paper, an enhanced Change Modes and Effects Analysis (CMEA) tool is presented for assessing product flexibility. The tool is designed to be more user-friendly and consistent than previous versions of a similar tool.

2. Related Work

Previous efforts to measure product flexibility are varied, partly because of the lack of a single consistent definition for product flexibility. Consequently, Shewchuk [5] suggests a generic metric that can be used by a designer to develop a personal flexibility measure based on his or her own view of flexibility. This rating system is therefore confined to a single designer or design team because the results would not be consistent between different users. Some other measures of flexibility are based on redesign effort, time, or cost [6]. There is a need for a measurement tool based primarily on manufacturing changes, because these are the bulk of the costs associated with a new product.

Jiang and Allada [7] approach the issue of changing customer requirements as a robustness design problem. They adapt the Taguchi methodology for improving robustness to this situation. This method evaluates entire product families rather than individual products, and it focuses on product functions instead of components. Jaikumar [8] and Das

[9] each look at flexibility with a focus on the manufacturing system as a whole. For designers who need to identify flexibility issues in individual products in order to improve their specific designs, these methods would not be applicable.

Martin and Ishii [10] 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." This method is limited because it considers only parametric changes, not changes related to added or altered functionality, i.e., adaptive, evolutionary, and revolutionary changes.

Several commonality indices have been developed to measure the degree of commonality in a family of products: Degree of Commonality Index [11], Total Constant Commonality Index [12], Product Line Commonality Index [13], Percent Commonality Index [14], the Commonality Index [15], Component Part Commonality Index [16], and the dendrogram approach [17]. Thevenot and Simpson [18] remark that commonality is measured to resolve the tradeoff between product commonality and increased manufacturing costs resulting from distinctiveness. These indices are used primarily for retrospective analysis of current or previous product families and focus only on commonality. They do not address product flexibility toward future evolutionary changes or consider 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 [19] have developed the Change Prediction Method (CPM) to analyze the effect of a change propagating through coupled parts or subsystems. The CPM is presented with the goal of improving the management of redesign efforts (by identifying design changes with high risk in terms of the number of affected subsystems). CPM therefore is used to react to existing inflexibility, rather than to proactively improve the flexibility of a design so it is easier to change at a later date.

The flexibility measurements listed above are useful in a variety of contexts and for a variety of goals. However, none of them provide a simple, repeatable method of measuring product flexibility at a level of detail that allows the user to derive actionable insights for improving product flexibility early in the design process.

Change Modes and Effects Analysis (CMEA) [20,21] is a tool for measuring a product's flexibility towards change and thereby diminishing the cost of redesign and shortening time-to-market. CMEA facilitates evaluation of products for flexibility for future evolution and comparisons of the flexibility of different products. Accordingly, it can be used to help identify characteristics of a design that inherently aid or hinder the flexibility of a product, thus pointing to innovative characteristics that may be added to improve flexibility.

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

In its original form, CMEA lacked full repeatability and a level of detail necessary for actionable insights into flexibility. In this paper, an enhanced version of CMEA is presented that is less subjective and more consistent when different users perform the analysis.

3. Research Methodology

The research approach for enhancing the CMEA methodology is summarized in Figure 2. The presentation of this methodology is important in understanding the foundation of the research and the systematic development of the CMEA.

The project began with the selection of a set of products for study, forming an empirical data set. These products were reverse-engineered for a deeper understanding of their functionality and architecture. Customer needs for these products were acquired through online customer reviews and interactive interviews, and were adapted into lists of potential future changes to the products. The CMEA methodology was enhanced through an analysis of the costly aspects of change and of potential methods for objectively quantifying them. As this enhanced methodology was developed, it was tested against the products in the study and hypothetical extreme cases. In the next section, the enhanced CMEA tool is presented, followed by an example application in Section 4.

[INSERT FIGURE 2.]

4. Enhanced CMEA methodology

In this section a methodology is provided for performing enhanced CMEA. CMEA is conducted using a table that is visually similar to the table used for Failure Modes and Effects Analysis (FMEA) [30,24]. 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 represent information related to the flexibility of the product to each change mode. The shaded columns are new to the enhanced methodology and are used to determine **Design Flexibility** more objectively than in the previous CMEA methodology. An explanation of the steps for conducting CMEA follows.

[INSERT TABLE 1.]

4.1 Preparing the CMEA table

Specific information about the product under analysis is required to perform CMEA. The user should be aware of all the product's components and functions (in their current design state or in the current product offering), and how the functions are performed. Additionally, a **function structure** of the product, or equivalent, should be mapped so its functions can be counted. Otto and Wood [22,24] provide a detailed explanation of a reverse-engineering process that would be suitable for determining this information if it is not available initially to the designer. The total number of functions is used in CMEA to normalize flexibility ratings based on the functional complexity of the product.

Next, a list of **Potential Change Modes** for 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 customer requirements can be found through surveys, interviews, customer reviews of similar products, research of competing or analogous products, and brainstorming means of improving the product. These changes should be inserted in the CMEA table.

The **Affected Components** column should be filled with a list of the components that will be altered or replaced for the change mode. Removed components are not counted because the cost of their removal is measured purely in terms of accommodating changes to neighboring parts. A **component** is defined as one of the following:

- A seamless part of one material designed by the product designer(s).
- A part purchased from and designed by another company.
- 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. Changes to the electronic logic of a product usually require changes to the circuit board. CMEA is not intended as a tool for measuring the flexibility of electronic circuit design, so the elements on a circuit board are not analyzed.

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

Next, three ratings are found for each of the potential changes, and these are used to determine a **Change Potential Number (CPN)** for each potential change. The enhanced CMEA methodology uses a new scale for the three ratings so they are easier to use and understand. All three ratings are on scales of one to ten, with higher numbers less desirable, analogous to the ratings of FMEA. 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 manufactures it. A one ("1") represents a potential change that requires insignificant redesign cost, and a ten ("10") represents a potential change that incurs extreme redesign cost.
- **Occurrence (*O*)** reflects the probability of a particular change occurring. Changes are categorized as either incremental (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 an incremental change, a one ("1") represents a change that is extremely unlikely to be implemented over a certain range of time (chosen for consideration by the CMEA user), and a ten ("10") 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 company can begin to implement the change in its manufacturing chain. This rating reflects only qualities that are specific to the particular company producing 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 ("1") represents a potential change that can be implemented immediately without restructuring cost, and a ten ("10") represents a potential change that the company cannot feasibly implement.

Of these three factors, Design Flexibility is the one over which designers have direct control. For the designer, Occurrence and Readiness can indicate which of the proposed change modes pose the greatest future cost risk, and therefore where Design Flexibility improvement efforts should be focused.

*4.2 Determining Design Flexibility (*F*)*

The enhanced methodology improves the determination of **Design Flexibility (*F*)**, because it requires counting specific modifications to the current components and assembly. This enhancement results in more consistent results between different users of CMEA, because they are based on an objective count of each of the significant contributors to redesign cost.

The ***F*** rating is on an integer scale from one to ten, where one is ideal flexibility and ten is complete inflexibility, based on the range of complexity of the products under consideration. The scale is reversed from the prior *F* scale [20,21,29] for two reasons: (1) to ensure that all three metrics, ***F***, ***R***, and ***O***, consistently represent undesirability with higher ratings, and (2) to parallel the three ratings of FMEA, in which higher ratings also represent greater undesirability.

The determination of ***F*** begins with completing the **Potential Effect(s) of Change** column in Table 1. The designer identifies the most likely means of implementing the change mode and explains how each component is affected (replacement, geometry, orientation, material, function, or assembly method). In the enhanced methodology, the nature of these changes is important for determining Design Flexibility, because each type of design change adds to the cost of manufacturing changes. When determining the Potential Effect(s) of Change, the designer should take care to consider only the most likely means of implementing the change mode; that is, the least costly known option, or the one affecting the fewest components. This choice is important, because if a poor implementation option is used, the product will appear less flexible to the change mode than it actually is. In the empirical study in the next section, engineering judgment was combined with results from team concept generation sessions to select the most likely implementation for each change mode. Although it is possible to implement multiple change modes together in a new product design, each change mode is considered independently to avoid the combinatorics and time-consuming task of analyzing every combination.

The affected components and assembly steps are tallied in the next six columns of Table 1. As a new feature of the enhanced CMEA, these six categories are selected because they represent types of redesign manufacturing changes of significant and approximately equivalent implementation effort, 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. Third-party components are components designed by and purchased from a company other than the one designing the product under analysis. 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 must be 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 omitted from consideration, so the product's flexibility rating is not penalized for potential changes that are inherent. Added components generally result from new functionality and are therefore inevitable, and removed components do not incur significant costs alone. The effect of adding or removing components on redesign cost is nevertheless present in the analysis if these changes affect interfaces on components that remain or already exist in the product. If adding or removing components does not affect any interfaces, then the associated flexibility is ideal and these changes justifiably should not affect the flexibility rating.

The next column to be completed in Table 1 is the **Changes-to-Function Ratio (*CFR*)**. The *CFR* is the total number of required component and 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 therefore a cost-of-change indicator that is normalized to the complexity of the product, so that products of varying complexity can be compared.

Designers must determine their own rubric for converting *CFR* into *F*. The purpose of a quantitative rubric for *F* is to define its one-to-ten scale, so the designer 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 designer expects to encounter. Then the designer will have an intuitive understanding of how to interpret an *F* rating.

[INSERT FIGURE 3.]

A proposed rubric is illustrated in Figure 3.The proposed rubric is based on an analysis of a product that the designer considers to have very poor flexibility. This product is 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 company 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 ten. An *F* of one represents ideal flexibility, which occurs when a change mode requires no redesign cost. Therefore, a *CFR* of zero should result in an *F* of one. A linear interpolation is used to assign ranges of *CFR* to each integer value of *F* from one to ten. This results in the following formula for *F*:

$$F = \text{int}\left[\frac{9 \cdot CFR}{CFR_{\max}} + 1\right] \quad (1)$$

For example, in the empirical study, CFR_{max} was 0.286. Therefore, a *CFR* of zero results in the following:

$$F = \text{int}\left[\frac{9 \cdot 0}{0.286} + 1\right] = 1 \quad (2)$$

A *CFR* of 0.286 results in the following:

$$F = \text{int}\left[\frac{9 \cdot 0.286}{0.286} + 1\right] = 10 \quad (3)$$

A *CFR* of 0.147 results in the following:

$$F = \text{int}\left[\frac{9 \cdot 0.147}{0.286} + 1\right] = \text{int}[5.63] = 6 \quad (4)$$

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* ratings of ten, but they indicate that the expected range of flexibility has expanded, so the designer should consider using a higher value for CFR_{max} to ensure that varying levels of flexibility can be differentiated. Designers may wish to use values of CFR_{max} from previous inflexible iterations of the product so that current products can be judged based on progress. Conversely, designers may find that if progress has been made in successive design iterations, the value for CFR_{max} is too high and should be lowered to improve the resolution of the Design Flexibility rating.

*4.3 Determining Occurrence (*O*)*

Occurrence (*O*) should be calculated based on the company's economic strategy and known customer requirements obtained from market projections, customer surveys, interviews, sales records, etc. First, the **Potential Cause(s) of Change** should be added to the CMEA in Table 1. 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." The Potential Cause(s) of Change is/are the factor(s) influencing the Occurrence.

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. *Incremental changes*—These changes may occur repeatedly 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: Increase motor power.

Opportunistic change *O* ratings can be based on how many times the drawback or opportunity appears in customer reviews and interviews, with a one representing a change that customers do not care about (and is therefore unlikely), and a ten representing a change that customers demand (and is therefore very likely). This mapping depends on the customer data available to the designer.

O ratings for incremental changes should be determined based on a rubric that considers how likely and how often a change mode will occur over a certain period of time. Rajan and coauthors [20,21] provide the metric in Table 2 as a generic rubric for time-dependent changes. It is based on how many times a change will occur in the next ten years of redesigning a product.

[INSERT TABLE 2.]

*4.4 Determining Readiness (*R*)*

Readiness (*R*) for a particular potential change should be determined by an investigation of the company's ability to accommodate the change in terms of manufacturing readiness, supply chain readiness, organizational readiness, and financial readiness. Whereas the Flexibility (F) rating reflects the design cost of fully specifying changes in the product and its manufacturing and assembly processes, the Readiness (R) rating reflects the cost, in terms of time and effort, of actually implementing the production changes. Since this internal corporate information is not readily available to those outside a company, each company must create its own rubric for *R*, based on these contributing factors. In the absence of this internal information for the products studied, *R* was omitted in the empirical product study. The reader is referred to Rajan and coauthors (2003) (2005) for more information regarding readiness.

*4.5 Determining the Change Potential Number (*CPN*)*

The final column of the CMEA in Table 1 is the **Change Potential Number (CPN)**. The CPN for a potential change is the product of *F, O,* and *R*. This method of calculating *CPN* is simplified from the previous CMEA formula, and is made possible by the changes to the scales for the three ratings. This simplified formula also parallels the formula for the *RPN* in FMEA, which increases the familiarity and intrinsic understanding of CMEA to those already familiar with FMEA.

5. Application of Enhanced CMEA to a Product

This section contains an example application of the enhanced CMEA methodology to an actual product, the Black and Decker TR1700 17” Hedge Trimmer, illustrated in Figure 4. Along with a diverse set of additional consumer products, the hedge trimmer was studied as part of the CMEA enhancement process [23]. The final CMEA table for this product is presented in Table A2 in the appendix, based on the customer needs and potential changes presented in Table A1. A step-by-step description of the CMEA process is provided in the remainder of this section.

[INSERT FIGURE 4.]

5.1 Reverse engineering the product

In the absence of detailed product information from the designers, the product was reverse engineered [24] to provide the necessary data for quantifying flexibility. The results of the reverse engineering process included a function structure and a bill of materials to represent the functions and attributes of each component, respectively. This procedure helped the researchers determine how potential change modes might be implemented.

As part of the reverse engineering process, a detailed investigation was aimed at understanding customer needs for the hedge trimmer. This understanding was obtained by researching the manufacturer's advertising for the product, interviewing potential customers, and analyzing online customer reviews of the product and its competing products. The interviews were conducted using the Like/Dislike method (articulated use method) described by Otto and Wood [22]. After each interview, all customer statements were translated into customer needs for the product.

Customer reviews of the product and its competing products from the websites Amazon.com and epinions.com were studied. Each product characteristic mentioned in a review was translated into a customer need for the product. The relative importance of each customer need was estimated based on the language context in the review. Eight interviews were conducted using the TR1700, and fifty online reviews of the TR1700 and other hedge trimmers were studied. This large number of reviews produced a list of customer needs so exhaustive that the last fifteen (or more) reviews did not yield any additional customer needs. The customer needs found for the TR1700 are listed in Table A1 in the appendix. The numbers in parentheses indicate the importance of each need on a one-to-five linear integer scale, where a one corresponds with needs that would delight some customers if met and a five corresponds with needs that customers absolutely demand from the product.

Another step in the reverse engineering process involved determining the overall function of the TR1700, which is to *cleanly cut hedge branches*. The overall function was determined based on the product packaging and customer expectations expressed during the customer needs interviews. Based on this overall function, a function structure diagram of the product's basic manipulations of matter, energy, and signals was predicted, as illustrated in Figure 5. The purpose of this *predicted* function structure was to provide insights into the designers' decisions by comparison with an *actual* function structure based on the internal architecture of the product, which was partially concealed within the housing.

[INSERT FIGURE 5.]

To meet the reverse engineering goals of predicting potential change modes and methods for implementing them, it was necessary to catalog all the parts in the product and to determine the function of each. A bill of materials for the product was created at a level of detail adequate for these goals. An excerpt from the bill of materials is shown in Table 3. The product was non-destructively disassembled to uncover all product components. Each component was cataloged in the bill of materials along with its functional purpose. The functional purpose of each component was determined by inspection, or, when necessary, by operating the product with the component removed.

[INSERT TABLE 3.]

In the final step of the reverse engineering process, a function structure of the product's *actual* manipulation of matter, energy, and signals was created, based on the disassembled product. As illustrated in Figure 6, the actual function structure was used as a representation of the complexity of the product when determining potential change modes. In comparison with the predicted function structure in Figure 5, it is evident that the gear transmission was not initially predicted. In a more complex product, a difference such as this could provide insight into alternate means of achieving the necessary functions of the product.

[INSERT FIGURE 6.]

5.2 Compiling a list of potential change modes

The first step in applying CMEA is to identify the potential change modes under consideration. The brainstorming method was used to create a list of potential change modes, both incremental and opportunistic, for the TR1700. Six mechanical engineers participated in the change-mode generation session. For each of the previously identified customer needs, the participants verbally suggested and discussed possible changes to the product to meet those needs better, creating new ideas and building off of one another's ideas. Shortcomings to the ideas were not discussed. One participant facilitated the discussion, guiding the topic under consideration and scribing notes.

It was important to produce both incremental and opportunistic potential change modes because flexibility towards different types of flexibility may be affected by different design characteristics. For many of the customer needs, both incremental and opportunistic solutions were suggested. For example, for the customer need "comfortable for left-handers" an incremental solution is "widen handles". An opportunistic solution is "add additional handles."

After the change-mode generation session, the concepts were filtered. When there were multiple solutions to the same customer need, only the most realistic were retained. Concepts that were technologically infeasible, extremely unlikely to be implemented in the next ten years, or inadequate at meeting the customer needs were removed. Some examples of removed concepts are the following:

- "Provide snap-on outer casings to choose from," for the customer need "aesthetically pleasing," was removed because it would be highly unlikely for customers to be willing to pay for new covers for a power tool just to change its aesthetics.
- "Add additional handles" and "widen handles," for the customer need "comfortable for left-handers," were removed because the product handles are currently symmetrical about the center of the product's weight, so they would not improve comfort specifically for left-handers.
- "Tighten tolerance between blades," for the customer need "cuts cleanly," was removed because it cannot realistically be applied. The blades are already biased against one another, so tolerance between the blades does not hinder the cutting action.

The remaining change modes were added in separate rows of the CMEA table in the **Potential Change Mode** column in Table A2.

5.3 Listing affected components for each change

For each of the change modes, the most likely method of incorporation was identified based on the reverse engineering data and estimation of the relative costs of potential alternatives. These methods of incorporation were detailed to the point of identifying the specific product components that would be affected by the change. Those components were added to the **Affected Component(s)** column of Table A2.

For example, for the change mode, "Change pressure switch into flip switch," it was reasoned that the parts shown in Figure 7 would be affected. The safety lock latch must be changed geometrically to accommodate the new flip switch motion, and the electric switch must be replaced with a different type of electric switch that can be flipped. The two covers must be changed geometrically because they mount the electric switch and safety lock latch and provide the guides for its motion. The hand switch itself is not listed as an affected component because it is not changed; it is simply removed.

[INSERT FIGURE 7.]

*5.4 Determining Design Flexibility (*F*)*

The method of incorporating each change mode, as described above, was entered into the **Potential Effect(s) of Change** column in Table A2. Based on this information and the list of affected components, potential changes in each of the six categories were counted and added to the table for each potential change mode.

For example, for the change mode, “Change pressure switch into flip switch,” the parts that are geometrically changed are the left and right covers (which must accommodate the mounting of the new flip switch, fill in the gap left by the pressure switch, and accommodate the new safety switch motion), and the safety switch (which must be redesigned to work with the new flip motion of the switch). The electric switch, which is purchased from a third party company, must be replaced with another switch that accommodates the flip switch motion. The geometrically changed parts do not require new material, and can continue to be injection molded. The assembly steps are not affected, because the new parts can be placed at the same stage of assembly as the parts they replace.

The ***CFR***s were calculated from these tallies and added to the table. Since the hedge trimmer was similar in complexity to five other products from the empirical study, the highest *CFR* across the six products (0.29) was used as CFR_{max}. Using this value, **Design Flexibility (*F*)** was calculated according to Equation (1). The use of the same CFR_{max} for the analysis of each of these six products allows straight-forward comparison of the results between similar products.

*5.5 Determining Occurrence (*O*)*

In the absence of marketing information and plans from Black and Decker, the **Occurrence (*O*)** ratings were based on the importance ratings of the customer needs associated with each change mode. The associated customer needs for each change mode were filled into the **Potential Cause(s) of Change** column in Table A2.

For opportunistic change modes, ***O*** was taken to be twice the importance rating of the associated customer need (which was measured on a 1-5 integer scale) with adjustments based on the suitability of the change mode as a solution. For changes that improve performance for multiple customer needs, a higher ***O*** was assigned, and for changes that decrease performance for some customer needs, a lower ***O*** was assigned. It is important that ***O*** not be influenced by the feasibility of a change mode, because feasibility is covered by the ***F*** and ***R*** ratings. Some examples of opportunistic change mode ratings are the following:

- The change mode, “Add an auto-brake,” is opportunistic because it provides new functionality. In the current product, inertia causes the blade to continue its motion for about a second after power is cut. The associated customer need, “Difficult to cut user,” has an importance of 5, but an auto-brake would not significantly reduce the speed at which blades stop, and therefore would not reduce the likelihood of user injury very significantly. Therefore, an ***O*** of 3 is entered.
- The change mode, “Switch to dual-motion blades,” is opportunistic because it alters functionality. In the current product, one blade is kept stationary while a second blade reciprocates. The associated customer need, “Minimal vibrations,” has an importance of 5, and dual-motion blades could significantly reduce vibrations, so an ***O*** of 8 is entered.

For incremental change modes, the rubric in Table 2 was used. The values for number of changes in ten years were estimated based on the importance ratings of the associated customer needs and the likely frequency of change of that particular customer need's target value. For example, the change mode, "Change blade length," is incremental because it alters performance without changing functionality. With each iteration of the design, the blade length may be changed. The associated customer needs are "Compact" (Importance: 4), "wider cutting area" (4), "low weight" (5), and "low cost" (5). Blade length may be shortened to lower volume, weight or cost, but it may be lengthened to widen the cutting area. Therefore ***O*** was estimated to be higher than it might have been for a single associated customer need. It is possible that the product will evolve into separate products, some with longer blades, and some with shorter blades.

*5.6 Determining Readiness (*R*)*

In the absence of internal operating data for Black and Decker, **Readiness (*R*)** was omitted from the hedge trimmer's analysis. If this analysis were being used by a company to study the products of other companies, it would be difficult to obtain useful data related to readiness without extensive benchmarking, so omission of ***R*** is possible. For a company studying its own products, ***R*** would be a useful means of identifying design characteristics, supply chain characteristics, or production characteristics influencing the flexibility of the product for future evolution. This information could then be used to improve the design, the supply chain, or production issues within the company. Through comparison of varying levels of **Readiness** for different products or even specific change modes for a single product, insights into the factors influencing **Readiness** could be made, so a strategy for improvement could be formed.

*5.7 Calculating the Change Potential Number (*CPN*)*

The **Change Potential Number** for each change mode was calculated as the product of ***F*** and ***O*** because ***R*** was omitted from the study.

5.8 Interpretation of results

The values in the ***CPN*** column of Table A2 can be compared to identify which change modes have the most influence on flexibility. Those with the highest values have the greatest negative impact on flexibility. Each row of the table can be examined independently and used to identify the factors influencing the redesign cost of any particular change mode. Accordingly, designers can identify specific design characteristics that should be revised for improved product flexibility and lower potential redesign cost. In addition, the CPN data can be used to compare the product's flexibility to other products of similar complexity from any manufacturer. This information would be useful for benchmarking a product against others and identifying characteristics of the design that affect its flexibility. Also, the results can be useful for identifying principles for improving product flexibility, in the form of features that tend to lower the CPN of a product, as detailed in Keese [23].

For the hedge trimmer, a change mode with a high ***CPN***, 64, is "Remove hand shield". This ***CPN*** is especially high because both the Design Flexibility and Occurrence are high. This means that the change will be both costly to implement and likely to be applied. If a designer of a new hedge trimmer were analyzing the Black and Decker product to gain insights to apply to the new design, the data from the row for this change mode could be used to identify the factors of the design that caused a large negative impact on flexibility. ***F*** is high because there are five costly results of the change mode. Three components must be redesigned; the assembly must be reordered; and the assembly method must be changed for one of the components. A lower ***F*** for a new hedge trimmer could be achieved if channels for possible future electronics and wires were included in the initial design. As a result, fewer parts would be forced to change to accommodate the new switch. ***O*** is high because the hand shield is bulky, which increases the size and weight of the product, two undesirable characteristics. The designer of a new hedge trimmer could focus on finding innovative ways to reduce the bulk so the ***O*** of this change mode would be lower.

If a designer were analyzing an early prototype of the hedge trimmer, these same insights could be used to improve the flexibility of the product before it goes into full production. In contrast, if a designer were *re*designing the Black and Decker product, it would be too late to avoid the high ***CPN*** in the current product iteration. However, for those parts that must be redesigned, changes may be incorporated that would reduce ***F*** and ***O*** for potential change modes for the following design cycle. For example, if the product had interior channels leading to the secondary handle, then the covers would not need to be redesigned to accommodate wires for the new switch on the secondary handle. Therefore, the product can be redesigned with a new hole in the cover (as shown in Figure 8), so in future design iterations of the hedge trimmer, the *F* for this change mode (and other change modes that might require electricity in the secondary handle) will be lower (because there will be one fewer part affected geometrically by the change mode).

[INSERT FIGURE 8.]

6. Conclusions

Prior to the work presented in this paper, a basic, repeatable method did not exist for measuring the flexibility of a product. Specifically, a metric was needed with a level of detail appropriate for deriving actionable insights for improving the flexibility of a product in response to unanticipated design changes. In this paper, an enhanced CMEA tool is presented to satisfy this need.

CMEA has been tested practically on several consumer products as part of a broader empirical study [23]. These products include electro-mechanical products with light-to-medium complexity and a range of energy forms: pneumatic, thermal, electrical, light, mechanical, and sound energy. CMEA produced useable results for each of the products studied, without modification.

CMEA's domain of application can be logically generalized beyond the products tested. The Design Flexibility (*F*) rating in CMEA is based on the number of significant cost contributors from parts affected by each change mode. The six categories of cost contribution in CMEA have been filtered from typical redesign costs to a variety of mechanical products, so they should adequately capture the redesign cost of typical changes to mechanical products. The Occurrence (*O*) ratings in CMEA are based on the designer's own rubrics in the two possible categories of change: incremental and opportunistic. Therefore, the designer can ensure that the Occurrence ratings will fit whatever type of product is being analyzed.

For these reasons, CMEA should not require modification for use on any mechanical products of light or moderate complexity. However, for very complex products, CMEA may be time-intensive. For these cases, it may be appropriate to modify CMEA for more direct application. One method might be to apply CMEA separately to individual modules in the product, followed by applying it to the whole product, treating each module as a component. This process would result in a hierarchy of analysis levels, which could separately represent the flexibility of each module, as well as the flexibility of the overall design, in terms of modularization and architecture.

CMEA has benefits for a designer in several situations. During the early stages of new product development, it can be used to evaluate alternative concepts for their relative levels of flexibility. It can also be used to evaluate similar products to identify potential ways to increase the flexibility of a new product. During a redesign process, it can be used to evaluate a baseline product to increase the flexibility of the redesigned version. Finally, CMEA can be used to benchmark a product's flexibility against those of competitors. In each of these applications, detailed conclusions about the factors influencing flexibility can be obtained from data in the enhanced CMEA table. As a result, CMEA enables designers to improve product flexibility and reduce redesign costs.

Acknowledgements

The authors would like to acknowledge the support provided from the Cullen Endowed Professorship in Engineering, The University of Texas at Austin and the National Science Foundation under Grant No. CMMI-0600474. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the sponsors.

Appendix

[Insert Table A1 and Table A2.]

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Figure Captions

Figure 1 Products with flexibility for future evolution

Figure 2 Research method flow

Figure 3 Proposed rubric for converting CFR *into* F

Figure 4 Black and Decker Hedge Trimmer TR1700

Figure 5 Predicted function structure of the Black and Decker TR1700

Figure 6 Actual function structure of the Black and Decker TR1700

Figure 7 Components affected by the change mode, "Change pressure switch into flip switch"

Figure 8 A change to the current cover that would improve flexibility in future redesign cycles

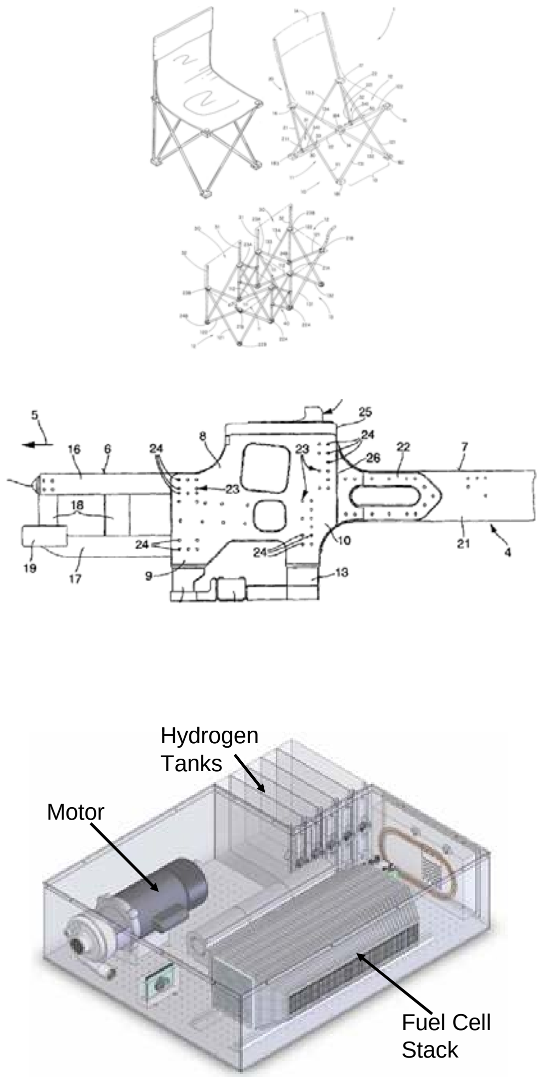

Figure 1 Exemplar products with flexibility for future evolution [25-28,4]

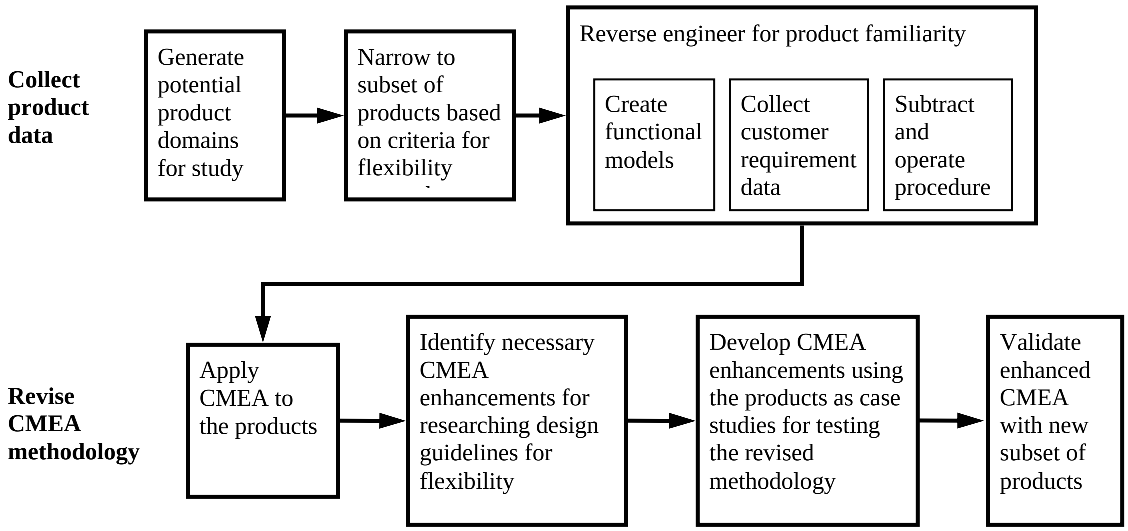

Figure 2 Research method flow

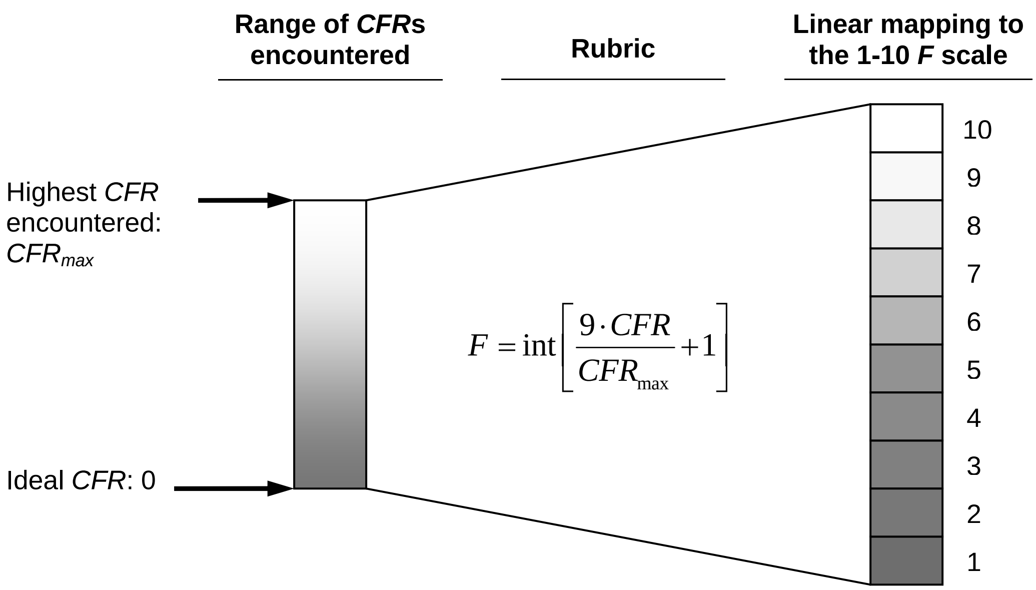

Figure 3 Proposed rubric for converting CFR *into* F

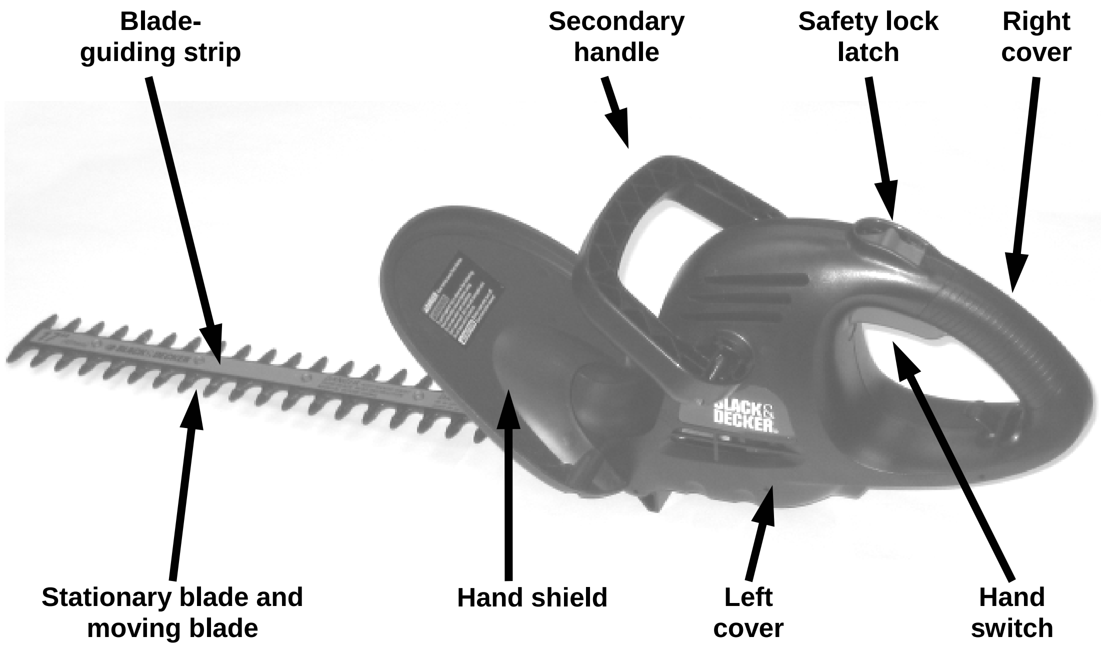

Figure 4 Black and Decker Hedge Trimmer TR1700

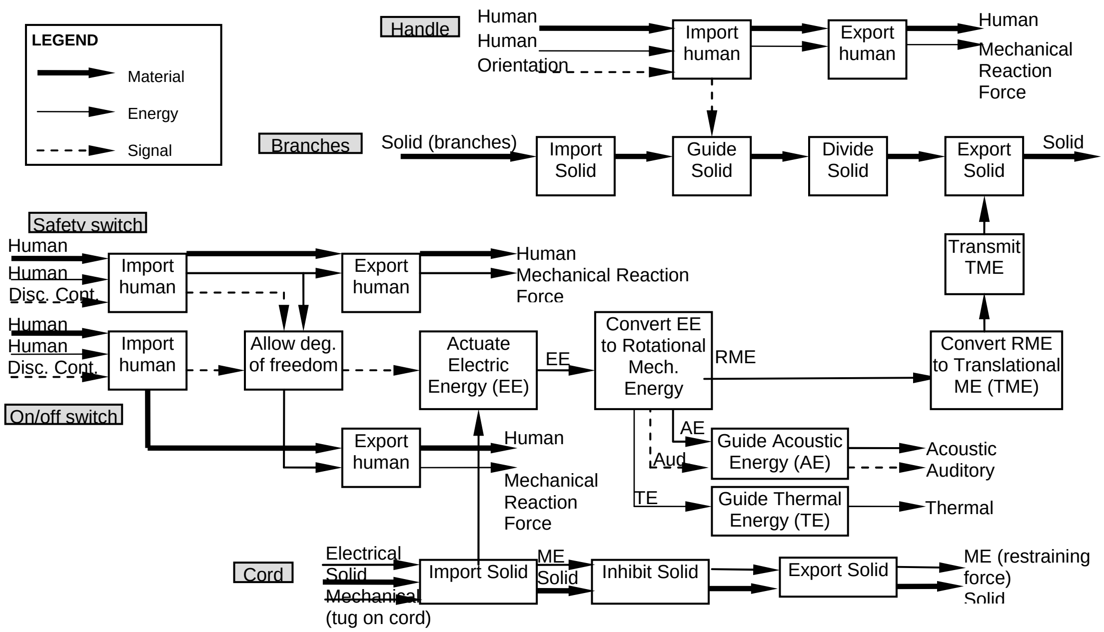

Figure 5 Predicted function structure of the Black and Decker TR1700

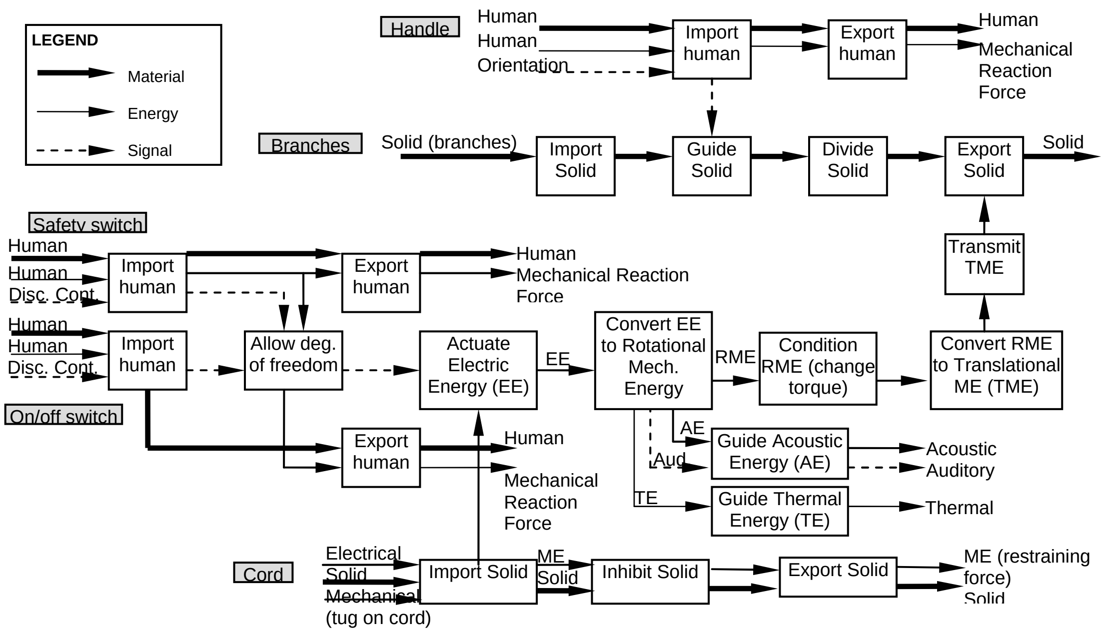

Figure 6 Actual function structure of the Black and Decker TR1700

Figure 7 Components affected by the change mode, "Change pressure switch into flip switch"

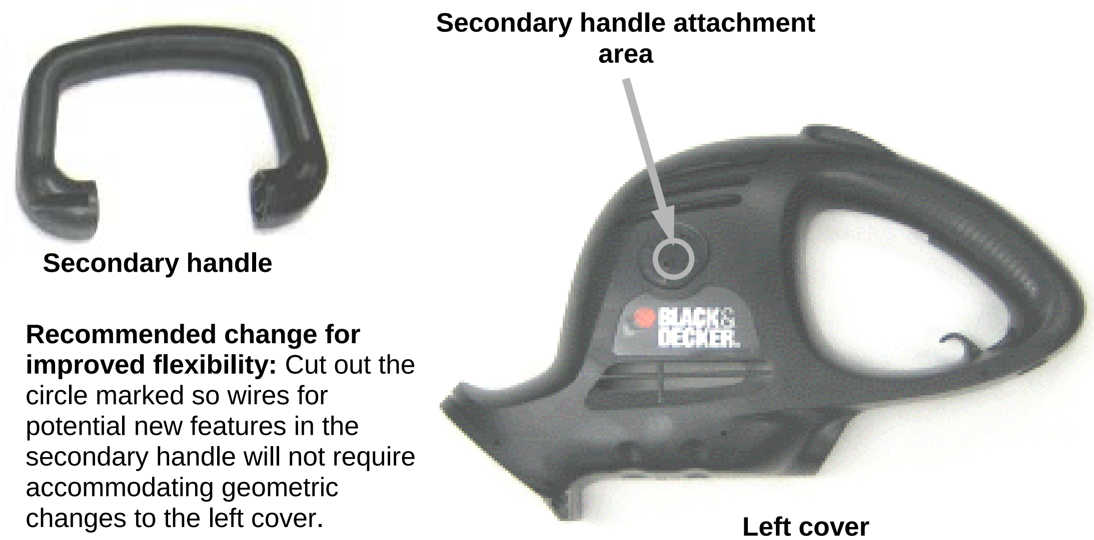

Figure 8 A change to the current cover that would improve flexibility in future redesign cycles

Table Captions

Table 1 Columns for a CMEA table

Table 2 A generic metric for determining Occurrence (O) for incremental changes [29]

Table 3 Black and Decker Hedge Trimmer TR1700 partial bill of materials

Table A1 Black and Decker TR1700 17" Hedge Trimmer customer needs and potential changes

Table A2 Black and Decker TR1700 17" Hedge Trimmer CMEA table (21 functions, $CFR_{max} = 0.29$)

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**

Table 2 A generic metric for determining Occurrence (O) for incremental changes [29]

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

Table 3 Black and Decker Hedge Trimmer TR1700 partial bill of materials

Part	Qty.	Description	Material	Color/ Finish	Mfg. Process	Effect of Removal	Function(s)
1	5	Blade-guiding bolt	Steel	Black	OEM	Moving blade becomes loose and cannot cut	Secure moving blade with stationary blade to guide motion
2	5	Blade-guiding washer	Steel	Black	OEM	Moving blade becomes loose and cutting performance is significantly reduced	Guide moving blade; reduce friction between moving blade and stationary blade and between moving blade and blade-guiding strip
3	1	Hand shield	Plastic	Black	Injection molding	No effect; possibly less safe for user	Deter user from injuring self by touching moving blade; push branches away from user's hand
4	1	Secondary handle	Plastic	Black	Injection molding	More difficult to control motion or use for extended period	Allow user to control unit with second hand
5	1	Right cover	Plastic	Black	Injection molding	Interior components come apart and are exposed and unit is completely inoperable	Secure interior components; protect interior components; provide user interface for holding unit; provide pivot attachment for switch user interface; allow heat venting for motor; provide cord retention force
6	1	Safety lock latch	Plastic	Orange	Injection molding	Unit cannot lock on; unit can be turned on without hitting a safety switch	Provide safety switch feature; provide lock on feature
7	1	Safety lock spring	Steel		OEM	Safety lock does not disengage; unit cannot be turned off	Automatically return safety lock to off position
8	1	Hand switch	Plastic	Orange	Injection molding	Cannot turn on or off because interior switch is inaccessible	Provide user interface for comfortable and convenient on/off; allow auto locking feature; allow safety locking feature

Table A1 Black and Decker TR1700 17" Hedge Trimmer customer needs and potential changes

Need	Importance	Potential Incremental Changes	Potential Opportunistic Changes
Aesthetically pleasing	2	Change color	Provide snap-on outer casings to choose from
Balanced weight	4	Shift cord plug to balance against blades across handhold points; change blade length	Make blade length adjustable; switch to rotary blade so its weight is closer to hands; make handle position adjustable; make blades swappable; add backpack power source
Blade covered for storage and transportation	2		Include plastic sheath for blade; include fabric sheath that doubles as a strap; add fold-down cover to main unit; make blade retractable; allow blade to fold up
Blades stay sharp	4	Increase cutting edge length; reshape blade to allow sharpening; change blade material and coating	Make blades self sharpening: add serrations and tightening screws; make blades customer-replaceable; include alcohol or sharpening liquid bath to store blade in; include cleaning sponge with oil/alcohol
Can be locked on	3		Switch to flip switch; make entire handle into a switch; add pulse monitor switch
Can be stopped quickly for safety	5		Include gloves that must be in contact with handles for power; add pulse monitor switch; add over-torque sensor; add brake clutch; add auto-brake to blades; add kill switch; remove auto-lock feature; require light pressure for continued power
Comfortable for left-handers	5	Widen handles	Add additional handles; make handles swivel
Comfortable to hold	5	Widen handles with multiple grip locations	Allow user to order custom-molded handle; make handles swappable; add additional handles for increased hold location options; add gel covering; add rubber covering; reshape casing for ergonomics

Need	Importance	Potential Incremental Changes	Potential Opportunistic Changes
Compact	4	Change blade length	Allow product to fold up; design product as modern art so it can be left in yard; make blade length adjustable; make unnecessary parts quick-connects
Cord does not pop out	5		Make cord retractable with different color near end as warning; add radios at both ends that detect distance of unit from wall socket; incorporate cord with hand grip; make the cord coiled and springy like old telephone cords; add a mirror for the user to see the other end of the cord; build the cord into the unit
Cord does not get in way	5	Orient cord to point down and away from blades; enlarge shield and make shield transparent so it does not block view of work area	Make cord retractable; add rigid cord guide that extends cord away from cutting area and user; include wearable attachment to clip cord to user's arm or shoulder
Cordless	5		Make product gas, battery, solar, wind, or fuel-cell powered
Cuts cleanly	3	Tighten tolerance between blades; reshape blades to curve to better lock branches in before snipping	Utilize spinning blades to slice through branches instead of sometimes cutting multiple times; diamond coat the blades; make the blade teeth double-edged
Cuts quickly	5	Scale motor	Include a gear train to tune the speed; utilize hybrid power or gas power; switch to dual-motion blades
Cuts thick branches	4	Widen space between cutting teeth	Add a small saw section with specialized teeth for larger branches
Difficult to accidentally start	5		Include gloves that must be in contact with handles for power; add a touch sensor switch; set an auto-lock to automatically disengage when power is lost; add a switch so contact of both hands is required

Need	Importance	Potential Incremental Changes	Potential Opportunistic Changes
Difficult to cut user	5	Enlarge shield and make it transparent so it does not block view of work area; reduce space between cutting teeth	Add a sensor for motion relative to movement that stops blades if there is unexpected motion; include two safety switches on separate handles; add a touch sensor switch on handle without switch
Durable	5	Scale motor; thicken material; change material; use more durable motor; increase fastening points	Remove unnecessary features
Easy to attach and detach cord	4	Reshape casing so the cord end is not recessed; locate plug so cord can be attached while one hand holds the unit by a handle	Redesign the socket and include specialized cord; make cord retractable; make cord built-in; add compliant clip
Easy to maneuver in all directions	4		Design product to strap to arm and add a wrist controller; add a new pivot direction; add blades; make blade freely rotatable; position handles so it is held like a sword; shape handles for a steering wheel grip; shrink product for precise control; add multiple holding positions
Easy to start	5		Switch to an on/off switch
Easy to store	4	Flatten end for easy leaning against wall	Add fold-out kickstand; allow disassembly into a small pile; make battery-powered with a wall charger that mounts it to the wall; add a lanyard loop for hanging on wall; add a hook; add a Velcro strap; add a hole at top for nail
Feels sturdy	2	Select heavier materials or increase bulk of parts; increase number fasteners; reshape casing for less empty space in product interior; change color to suggest sturdiness; stiffen handles	Reduce number of parts by integrating features; locate grips at high density areas
Fits standard power cord	5	(no change necessary)	
Fits various hand sizes	4		Make handles quick-connects and offer multiple shapes; add gel grip; add foam grip

Need	Importance	Potential Incremental Changes	Potential Opportunistic Changes
Long reach	4		Make head pivot; add a quick-connect pole extension interface; add a screw-in pole extension interface; add a telescoping pole extension interface; design product to balance across shoulder and reach farther; utilize piezoelectric blade; separate motor section from power/handle section by an extendable pole
Low cost	5	Scale parts	Remove features; change power source
Low weight	5	Scale parts down	Make power source strap to body; remove excess features
Minimal user assembly required	4	Reshape to eliminate dangling parts; remove long protrusions	Design protruding parts to fold in
Minimal user maintenance required	4		Minimize part contact; utilize rolling contacts; electro-coat parts; include blade sheath with oiled sponges inside
Minimal vibrations	5	Reshape handles to dampen vibrations transferred to user	Change linear motion of blades to rotational motion; change blades so they both move in opposing directions
Powerful	5	Scale motor; tune for reciprocating mechanical advantage	Use gas power; add gear train to tune power; use hybrid power
Quiet operation	5	Scale motor	Add a muffler; add active sound reduction speakers
Wide cutting area	4	Lengthen blades; broaden blades	Add a pair of blades in another direction; make blade swing or slide side to side; make cutting edge perpendicular with a sliding motion

Table A2 Black and Decker TR1700 17" Hedge Trimmer CMEA table (21 functions, CFR_{max} = 0.29)

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	Aesthetically pleasing	3	-	3
-	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	Blades stay sharp	3	-	12
-	Add liquid bath for blades	None	-	-	-	-	-	-	0	1	Blades stay sharp; minimal user maintenance required	2	-	2
Left cover, right cover, safety lock latch, switch	Change pressure switch into flip switch	The casing must seal the gap from the removed pressure hand switch and auto-lock latch, and provide a new gap for the new flip switch. The casing must also provide mounting for the new hand switch and the new electric switch. The safety lock latch must be altered to work with the flip switch.	1	3	-	-	-	-	0.19	7	Can be locked on	5	-	35

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 cover, right cover, safety lock latch, hand switch spring, stationary blade, moving blade	Add an auto-brake	New brake mechanism is connected to the safety lock latch interface and mounted into redesigned casing. The spring must be swapped for a stronger spring and the blades must be lengthened to provide a location for the brakes to contact.	1	5	-	-	-	-	0.286	10	Difficult to cut user	3	-	30
Hand switch	Remove auto-lock feature	Change the hand switch to prevent it from auto-locking with the safety lock latch.	-	1	-	-	-	-	0.048	2	Difficult to cut user	6	-	12
Left cover, right cover	Add rubber grips to handles	The handle area of the casing and secondary handle should be changed so they can accept an adhesive rubber grip.	-	3	-	-	-	-	0.143	5	Comfortable to hold	4	-	20
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; wide cutting area; low weight; low cost	5	-	20
Left cover, right cover	Add rigid cord guide	This guide can be an extension of the casing, or it can be a new part that affixes to the casing. In either case, the design change to the existing casing is similar: a location for the cord guide must be chosen and match up with the plug. The casing must support the weight of the guide.	-	2	-	-	-	-	0.095	4	Cord does not get in way	7	-	28

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 cover, right cover	Add quick-connect 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	Long reach	1	-	4
Left cover, right cover, stationary blade, moving blade, large gear	Switch to dual-motion blades	The ends of both blades are changed. The large gear is changed so a new mechanism controls both blades. The casing's mounting for the bottom blade must be altered.	1	4	-	-	-	1	0.286	10	Minimal vibrations	8	-	80
Left cover; right cover; 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	Durable, low cost, powerful, low weight, quiet	4	-	32
Left cover; right cover; safety lock latch	Remove safety lock latch without removing auto-locking feature	The safety lock latch can be redesigned so it does not lock. The safety lock latch is removed and the gap in the casing must be covered.	-	3	-	-	-	-	0.143	5	Low cost; easy to start; durable	3	-	15
Left cover; right cover; secondary handle	Add second required switch to secondary handle	The secondary handle must provide mounting for the new hand switch and new electric switch. The covers must allow for wire to pass from it to the secondary handle.	-	3	-	-	1	1	0.238	8	Difficult to cut user	1	-	8

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 cover; right cover; 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 filled in.	-	3	-	-	1	1	0.238	8	Low weight; compact (this part not necessary if a secondary switch is added)	8	-	64
Left cover, right cover	Add pivot feature	The handles and switches must be moved into a new pivot module. The casing must accommodate the new pivot module and provide a lock and release and a rotational mounting. The switches themselves do not require change if the new pivot module provides similar mounting.	-	2	-	-	2	-	0.19	7	Long reach	6	-	42