INTERNATIONAL CONFER ENCE ON ENGINEERING DESIGN
ICED 03 STOCKHOLM, AUGUST 19-21, 2003

DESIGN FOR FLEXIBILITY – MEASURES AND GUIDELINES

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Keywords: Product flexibility, Design for Flexibility, Failure mode and effects analysis, Measurement, Empirical study.

1 Introduction

Product flexibility can be defined as the *degree of responsiveness (or adaptability) for any future change in a product design*. Making a design more flexible leads to a reduction in redesign cost. Product flexibility plays a significant role in responding faster to customer feedbacks by allowing quicker updates in the products and achieving higher levels of performance in a short span of time. Despite this importance, flexibility definition and measurement in practice remains a difficult task. When considering the efforts taken in the past, to understand and measure product flexibility, few metrics have been developed. Such measures are based on time or cost required to redesign [6, 12]. In comparison of Flexible manufacturing systems in Japan and US, Jaikumar (1986) uses the number of new parts introduced per year as one of the measures of product flexibility. These measures were developed keeping manufacturing as the main focus rather than the product itself. This paper presents an alternative understanding of product flexibility from a design perspective. Using an empirical study foundation, the main objectives of this research is to develop a method to evaluate flexibility of product design, and derive a set of guidelines to guide product architecture to a desired state of flexibility.

2 Methodology

This research includes three primary components: an initial empirical study, a flexibility evaluation method that is analogous to Failure Mode and Effects Analysis (FMEA), and a validation process. These three components are discussed in the following sections.

2.1 Initial Empirical study

The initial empirical study focused on the dissection of a varied range of consumer products on the market. This descriptive study involves observation, measurement and analysis of the product for various factors that might influence, directly or indirectly, the flexibility. In this study we found that factors such as number of parts, functions, standard (OEM) components, modules, and way these modules are arranged in a design, interfaces and the type of interfaces all influence flexibility of a product. Based on this initial study, and because of the complexity of this problem, we focused on questionnaire-based methods involving human science to study and measure the flexibility of products.

2.2 Change Mode & Effects Analysis (CMEA)

An established industry method FMEA (Failure Mode & Effects Analysis) provides a good first analogy to evaluate product flexibility. FMEA is a systematic approach that identifies potential failure modes in a system, product, or manufacturing operation caused by design or manufacturing process deficiencies. FMEA is a tool used to prevent problems from occurring. Instead of evaluating the failure modes as we do in FMEA, we propose to evaluate possible future changes in a product. This method is explained as a two step procedure as follows:

***Step 1: Decomposing the product*:** The preliminary step in this process is to decompose the product in some rational manner so that it can be assessed for possible changes. Depending on the complexity of the product under study, this decomposition can be done with respect to functions, parts or modules. In this paper we choose to decompose products using modules and parts. Decomposing the products based on the functions [4] will be of more help in the conceptual design stage where we are not sure about the final form of the product.

Step 2: Forming the CMEA table: The second step in this method is to assess the 'Change Potential Number' (CPN) for a product for possible changes. The 'Change Potential Number' gives an indication of how easily a change can be incorporated in a product. CPN is the overall flexibility for a given change. The inherent flexibility of a design for a given change, the probability of occurrence and the readiness of the company to react to this change are the main factors that are considered to evaluate CPN. In this section we propose a systematic way of doing this analysis. The CMEA table shown in Table 1 is used to perform this analysis.

Table 1. Generic CMEA basic columns

CHANGE MODE AND EFFECTS ANALYSIS FOR POTENTIAL CHANGES IN PRODUCT DESIGN							
Modules / Parts	Potential change Mode	Potential Effects of change	Design Flexibility	Potential Cause(s) of Change	Occurrence	Readiness	Change Potential Number

The basic columns in the CMEA table are shown in Table 1. Design flexibility, Occurrence and Readiness (which are highlighted) are the three main metrics used to determine the CPN of the products. The other columns are supportive columns to help the designer access these three main metrics. The basic columns in this table are explained as follows:

Modules/Parts: This column might be parts or functions or subassemblies depending on the complexity of the product under study. As explained in the above section this is dependent on decomposition of the product.

Potential causes of change: The potential causes of changes for a particular module or part are documented in this column of the CMEA table. The potential causes of the changes can be obtained from the following: a) customer reviews or customer needs of the products, b) from a group of experienced designers in that product segment, c) performance goals for the company, market pressure to improve the variety etc.

Potential changes: In this column of CMEA table the potential change(s) that a particular module or part can possibly undergo is documented in terms of the parts and the changes involved with these parts and their functions. For example consider a module in a device say a DC motor. A possible change might be to increase or decrease motor power.

Potential Effects of change : The various effects of a particular change over the other parts or functions of the device are documented in this column after a brief brainstorming session by the designer. This can also be seen as the ripple that this change causes to the other related parts and functions in the device. For example in our previous example of a DC motor, let us assume that the team decides to increase the size of the motor. Because of this change the housing of the product might have to be changed because of the geometric dependency of the motor with the housing.

Design Flexibility: In this column of the CMEA table, based on the potential effects of the change from the previous column, the extent to which this change will affect the entire product is assessed and rated against an interval scale [4] of 1-10. Where '1' means the minimum flexibility and '10' means completely flexible. The product with high flexibility ranking means, for any future change the redesign cost is low. As shown in Table 2 a table for rating the flexibility can be followed throughout the study. A generic CMEA flexibility table is shown in Table 2. This table was followed throughout our empirical study.

Table 2. Generic CMEA design flexibility.

Effects	*Criteria: Flexibility of the design for a change*	*Ranking*
New product	Very low flexibility ranking when there is a total redesign (no reuse of parts) of the product, which involves redesign of every single module or component in the product.	1
Total redesign with some reuse of parts	Very low flexibility ranking when there is a complete redesign or replacement of all most expensive modules in the device that involves substantial cost incurred.	2
Very high level of redesign	Low flexibility ranking when there is a redesign or replacement of more than one expensive module in the device.	3
High level of redesign	When there is a redesign or replacement of a module, which involves major manufacturing cost.	4
Moderate redesign	When there is a redesign or replacement of a module, which involves considerable manufacturing cost.	5
Low change	When the change involves both parametric and minor adaptive redesign involving considerable cost.	6
Very low change	High flexibility ranking when there is only a major parametric change in the parts.	7
Minor	Very high flexibility ranking when there is a minor parametric change in the parts, which can be achieved in very less cost.	8
Very Minor	A very trivial change which involves almost no cost incurred.	9
None	No effect	10

Occurrence: This column of the CMEA table is based on the 'Potential causes of changes' column. The probability of occurrence of these changes is assessed on an interval scale [4] of 1-10 where '1' means no or relatively few occurrences and 10 mean that the change is inevitable. Therefore a product with low Occurrence ranking means, the probability of any future change occurring in that design is minimal, which in turn leads to a less redesign cost. So a product with low Occurrence ranking is more flexible. This probability of occurrence may be determined based on the rate of occurrence of these particular changes. These changes can be broadly categorized as follows:

1. *Drawbacks or opportunities in the present design.* These changes can be ranked on a scale of 1 to 10 based on the number of times they occurred during the customer review.

2. *Time-dependent change*. These changes include how technologies change over time, the company's futuristic plans in the evolution of this product, and future expectations from the customers on the performance envelope of these products.

Shown in Table 3 is an example of a generic CMEA occurrence table for rating the time dependent changes. One can roughly estimate the rank for Occurrence as equivalent to the number of expected changes in 10 years. Of course, Table 3 is just an example of an approach that a company may adopt; other approaches to identifying the value for Occurrence may depend upon the type of product and its environment.

Table 3. Generic CMEA Occurrence

Probability of Occurrence	*No of times in every 10 years*	*Ranking*
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: In this column of the CMEA table, the readiness of the company for this particular change is assessed and rated against an interval scale [4] of 1-10 where '10' means the company is completely prepared to go ahead with this change and '1' means that the company is completely unprepared for this change. This implies that the product with high Readiness ranking means, for any future change the redesign cost incurred is low. Therefore a product with high Readiness ranking is more flexible for a given change when compared to its counter part. The factors to be considered during ranking Readiness are elaborated in Table 5. An example of a generic CMEA readiness table is shown in Table 4.

Table 4. Generic CMEA Readiness

Readiness	*Ranking*
Completely prepared	10-9
High	8-7
Moderate	6-5
Very low preparedness	3-4
Completely unprepared	2-1

Table 5. Factors to be considered to assess Readiness

Factors	*Explanation*
Manufacturing flexibility	Company A having more flexible machines like machining centers and CNC's will be more flexible when compared to a company B with dedicated stand alone special purpose machines.
Supply chain flexibility	If company A has more than one supplier for a particular module when compared to company B then the former is more flexible when compared to the later. This might include flexibility of the company in terms of their supplier relationship. For example if its going to take company A to make his supplier change his product with in a short period of time without much resistance from him, then company A is more ready for this change. This will help them to make their changes in the modules faster.
Organizational flexibility	Company A's organizational structure can react to a change very fast when compared to company B.

Financial readiness	A large manufacturing company A will be more robust enough(in a financial point of view) for a change when compared to a small scale manufacturing company B, where the latter cannot afford for this change in a short period of time.

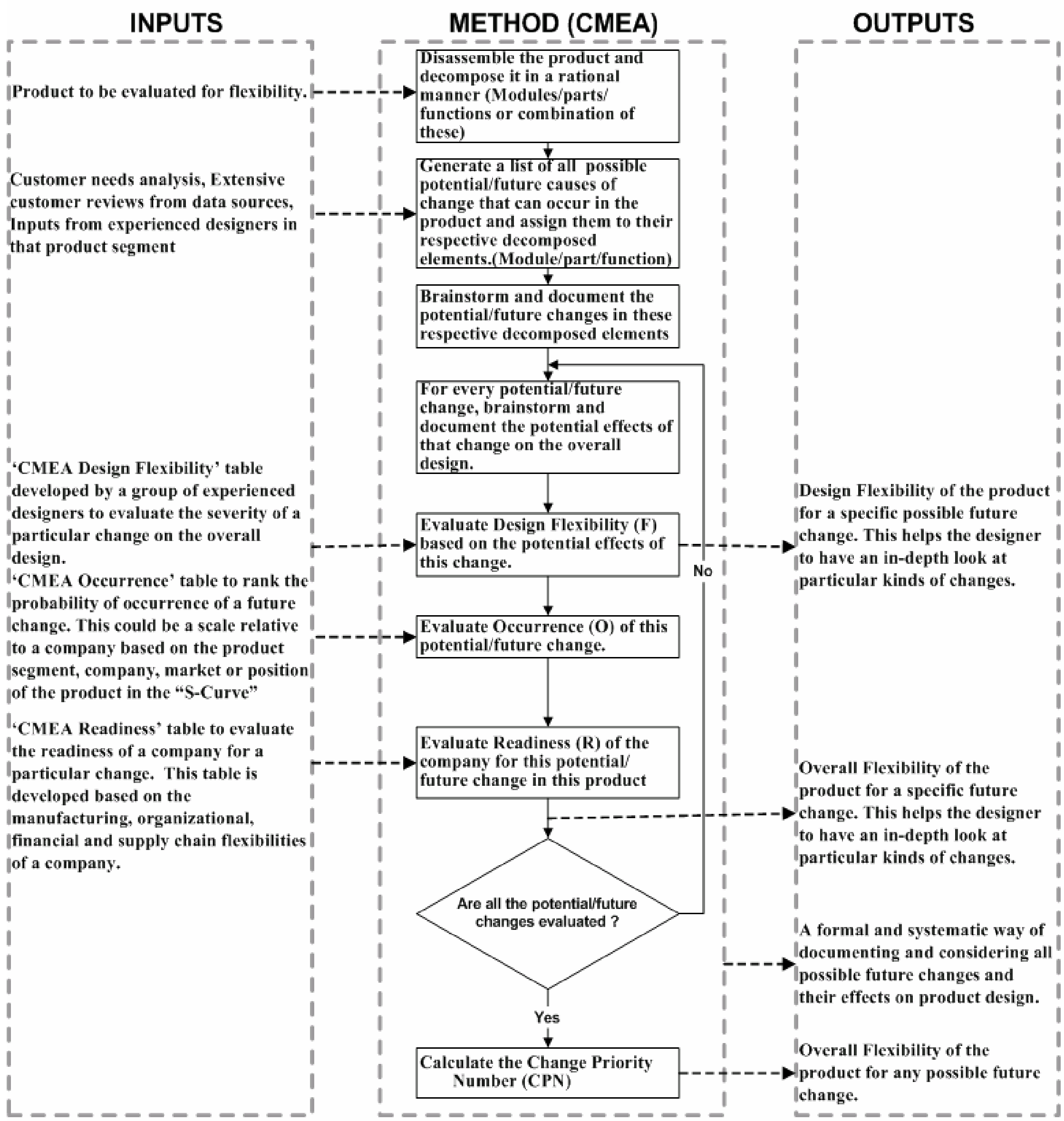


Figure 1. Change Mode and Effects Analysis (CMEA) Method Sequence of Operations Flow Chart

Change Potential Number: The CPN is defined as follows:

$$CPN = \frac{1}{N}\sum_{i=1}^{N}\frac{[(Ri + Fi) - Oi + 8]}{27} \qquad (1)$$

Where, F is Design flexibility, O is Occurrence, R is Readiness and

N = Max of (number of potential Change modes, number of potential effects of change, Number of potential causes of change).

The minimum value that the CPN can hold is '0' which means that the product is completely inflexible for any change and '1' means that the product is completely flexible for any future change. So based on this formulae a completely flexible product is a one in which the redesign cost incurred is 0$ for any future change in the design. The accuracy of these metrics was evaluated by conducting simple sensitivity analysis of these three main factors namely design flexibility, occurrence and readiness. The errors in assessing the three main metrics were assumed to be ± 1, on an interval scale of 1 to 10. Using this premise, the overall flexibility sensitivity is ± 0.11.

Illustrative Example

In this section we describe the CMEA method applied to B&D Jigsaw (Figure 2). The sequence of operations to be followed for this CMEA method is explained in Figure 1.

Figure 2. B&D Jig Saw

Step 1: Decomposing the product: The product understudy is disassembled and a list of components and modules are noted down in 'Modules/ Parts' column of CMEA table.

Step 2: Forming the CMEA table: The Change Mode and Effects Analysis on this B&D Jigsaw is shown in Table 6. This process of forming the CMEA table is explained as follows. The first step in this process is to gather the customer needs by studying extensive reviews from data sources (e.g. www.amazon.com, www.epinions.com). These reviews may indicate deficiencies in the current design, which are often the stimulus for a company to redesign its product. Therefore, we classify such stimuli as 'Potential causes of change', which occupies a similar column in our CMEA table as the 'Potential causes of failure' did in FMEA. It is important that these potential causes be assigned to the modules within the product that pertain to the customer identified problem. It is possible that a potential cause could impact the redesign of more than one module. After this process the potential changes in the respective modules are brainstormed and documented in the 'Potential change mode' column. Based on the suggested change in a particular module, the propagation of this change to the other modules of the design is brainstormed and documented in the 'Potential effects of change' column.

Based on this analysis and with the help of Table 2, the design flexibility (F) ranking for the particular change in the design is assigned. In the jigsaw example in Table 6, consider the 'Base Assembly' where the 'Potential change mode' is 'Change in the foot print area of the base plate' and 'Potential Effect of change' is 'This change will lead to modification in the housing'. Since the housing is an expensive module because of the cost in creating a new die, it is indicated as a 'High level of redesign' according to Table 2. Assessing the occurrence (O) of a particular change requires more rigorous customer reviews and opinions of experienced designers in the power-tools product segment. In this study in order to assess the occurrence (O) of these 'Potential cause(s) of change' the collected customer needs and reviews were ranked based on their importance and number of times they occurred during the data collection process. This rating was then used to assign the ranking for the occurrence (O) column in the CMEA table. In the absence of information on a company's manufacturing facility, supply chain network, organizational flexibility and operational flexibility it is difficult to assess the readiness (R) of a company for a particular change in their product. Even though we did not have a rigorous basis for assigning the readiness (R) for a particular change, in order to demonstrate this method we used a rough basis for providing the ranking in Table 6. This ranking was based on the size of the company. In Table 6, the readiness (R) ranking for a change in the 'Base Assembly' of B&D Jigsaw was assessed as '10' as Black & Decker is a more robust company when compared to a small scale manufacturing company. So Black& Decker will be more ready to make this change when compared to its counter part. Finally, the CPN for this product is calculated using the formulae in Equation 1, where N is the number of potential change modes in this example.

Table 6. Partial CMEA on B&D Jigsaw

CHANGE MODE AND EFFECTS ANALYSIS FOR POTENTIAL CHANGES IN PRODUCT DESIGN							
Modules / Parts	***Potential change Mode***	***Potential Effects of change***	***Design Flexibility***	***Potential Cause(s) of Change***	***Occurrence***	***Readiness***	***Change Potential Number***
Base Assembly	Change in the foot print area of the Base plate	This change will lead to the modification in the housing of the device	4	Instead of cutting smoothly through wood it has a tendency to jump around, particularly in plywood. Improve the stability of the device when using it. Improvement in the ergonomics, Device won't lock down at the different angles.	10	10	0.44
Blade support roller assembly	Change in parameters, materials or design variables	No effect on other modules in the device	7	The saw is not kept straight enough during the operation of the device.	5	10	0.74
No of potential change mode	*16*						0.62

2.3 Validation of CMEA

In order to validate the proposed technique, we decided to conduct an empirical study on a set of products available in the market. A set of 10 products, are chosen and differentiated as flexible and inflexible by experienced designers. The group of products which are chosen as flexible had multiple external modules, whereas the inflexible group of products had more integral design with fewer modules. These products considered for this experiment, ranged from small scale to medium scale consumer products. Shown in Table 7, is the set of products, which were evaluated using CMEA on a pair wise basis. In this table, for each pair of products the first product was considered more flexible when compared to the second product. So in the very first pair the B&D Jig Saw was considered to be more flexible when compared to the Braun coffee grinder. In this comparative study, out of the three factors namely design flexibility (F), occurrence (O) and readiness (R) only design flexibility was considered while comparing these products. In order to address all three of these factors, a significant level of industrial interaction is required. Given the constraints we choose to evaluate the products with design flexibility (F) alone. The flexibility ranking for these set of products are shown in Table 7. Based on this analysis, we can clearly see that the CMEA captures the difference in the design flexibility (F) of these products when comparing them on pair wise basis.

Table 7. Pair wise comparison of Products using CMEA

No	*Product*	*Design Flexibility*
1	B&D jig saw	0.51
2	Braun coffee grinder	0.27
1	Dustbuster B&D	0.49
2	Arrow light duty stapler	0.19
1	Handiwork Screw driver	0.44
2	Stanley Screw driver	0.22
1	B&D Electrical Knife	0.44
2	OXO Good Grips Knives	0.13
1	Sanford multipurpose pen	0.39
2	Disposable pen	0.17

3 Discussion on CMEA

The CMEA technique does not limit the view of product flexibility to manufacturing constraints, since flexibility in CMEA encompasses various aspects such as supply-chain, lifecycle, and as well as other design issues. In terms of end users, this technique is a formal and systematic way of documenting and considering all the possible future changes and their effects on product design. This helps the designer to identify and focus on areas which are more susceptible to future redesign, which in turn will lead to high redesign cost. As a systematic approach, the CMEA parallels and formalizes the mental discipline that a design engineer goes through in any product development process. CMEA is very useful when a designer needs an in-depth look at particular kinds of changes. One of the interesting advantages of this method is conducting comparative studies on product flexibility between competitor's products. This helps the company to identify opportunities and ways to improve their design, in order to reduce redesign cost, when compared to their competitors.

While evaluating factors such as occurrence (O), a rigorous (time intensive) customer review will give more accurate results. Similarly while measuring the readiness (R) of a company, considerable amount of time is required to evaluate the factors affecting it with respect to a particular company, as they are not readily available. These limitations might make this method a more time intensive when compared to FMEA. This indicates a need for a 'generic metric' where the designer simply takes measurements of certain physical parameters from a product that is known to correlate with flexibility. This method might not be as accurate as CMEA but it might be less time intensive, and can be used for conducting quick comparative study on small set of products.

4 Guidelines

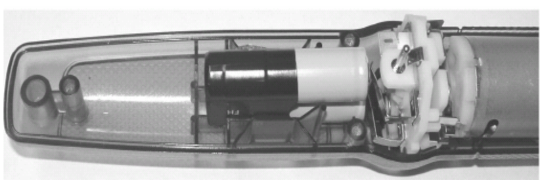
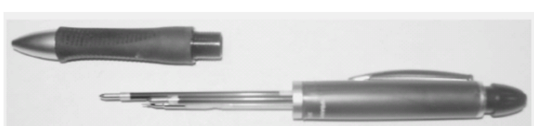
From the study conducted on the above set of products a set of guidelines were derived to improve flexibility of product design. These guidelines [5] are listed as follows:

1. Improve the design flexibility by making the device more modular.
2. Reduce the effect of a change in a design by increasing the number of partitions. This will lessen the impact of any individual element on the whole if a change becomes necessary for the element in question.

3. Reduce the effect of a change by increasing the number or size of virtual or actual buffer zones.
4. Reduce the occurrence of a change by increasing the performance envelope of the device
5. Reduce the occurrence of changes by standardizing components and interfaces.
6. Reduce occurrence of changes by selecting technology which is far from obsolescence.

Examples of flexible products that appear to use such guidelines are listed in Table 8.

Table 8. Examples of products using product flexibility guidelines

Product	*Explanation*
	The Bissell vacuum systems use multiple external modules. (Guideline 1)
	The Skill twist screwdriver exhibits a large amount of void space in the battery compartment. Additionally, this device demonstrates the use of standard OEM parts (NiCd batteries and the motor) which also happen to be the technology that is probably far from obsolescence. (Guideline 3,5,6)
	This pen has a higher performance envelop than a typical pen due to the three modes of writing – black ink, red ink and pencil. (Guideline 4)

5 Conclusion and future work

This research explores the definition of product flexibility, how it can be measured, and how one can design for flexibility. In addition, this work demonstrates how FMEA can serve as a useful analogy to address the problem of evaluating product flexibility. The potential advantages of these findings include the utility of Change Mode and Effects Analysis as a systematic aid in understanding how some future change might affect a product. Comparative studies and benchmarking efforts are two applications that can directly benefit from this work. This research develops flexibility guidelines so that designers can both evaluate a product and manipulate the design based on the results gathered from CMEA in terms of flexibility. Some departure points for future work is to find the correlation of the different physical parameters in a product, like number of parts, functions, modules, interfaces and type of interfaces, with respect to flexibility. This would lead to a more generic and less time intensive method to evaluate product flexibility.

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