Proceedings of DETC ‘04:
ASME 2004 International Design Engineering Technical Conferences
And Computers and Information in Engineering Conference
September 28th-October 2nd, 2004, Salt Lake City, UT

DETC04/DTM-0000

EMPIRICAL STUDY OF PRODUCT FLEXIBILITY

Palani Rajan P.K.
Manufacturing Engineer
Applied Materials, Inc.
Austin, TX 78754
K_palanirajan@mail.utexas.edu

Mike J. Van Wie
Department of Mechanical Engineering
The University of Texas at Austin
Austin, TX 78712
mjv@mail.utexas.edu

Kristin L. Wood
Department of Mechanical Engineering
The University of Texas at Austin
Austin, TX 78712
wood@mail.utexas.edu

Kevin N. Otto
Vice President
Leveraged Development
Product Genesis, Inc.
Kevin_otto@productgenesis.com

Matthew I. Campbell
Department of Mechanical Engineering
The University of Texas at Austin
Austin, TX 78712
mc1@mail.utexas.edu

ABSTRACT

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 potential reductions in redesign cost. When considering the efforts taken in the past to understand product flexibility (and develop associated metrics), most prior research focuses on the manufacturing domain rather than the product itself. In this paper, we investigate the physical factors that affect product flexibility. This study focuses on conducting an empirical study of existing products in the market. The physical characteristics, such as the number of parts, functions, interfaces, type of interfaces, modules, the way these modules are arranged, and OEM parts, are found to directly affect product flexibility. From these factors, guidelines are derived to improve product flexibility and design for it. This research is a significant advancement, leading us toward our future objectives of developing a generic flexibility metric and generative design method.

1.0 INTRODUCTION

Product flexibility should be considered in product development due to the changing nature of competition, constant improvements (evolution) in the performance and functionality of products, and the transient and multi-modal nature of customer needs. Despite these considerations, product flexibility remains poorly understood in theory, and poorly addressed in practice. Few metrics have been developed to measure product flexibility. For those that do exist, the measures are based on factors such as the time required to switch from one part mix (combination of parts) to another, the adaptability of a manufacturing system to changes in part mix and the number of new parts introduced per year. These measures were developed with a focus on manufacturing. In this paper, we study the fundamentals of product flexibility by correlating flexibility with different physical characteristics (such as number of parts). A “snapshot” of product flexibility is gained through this empirical evaluation. This snapshot addresses the main objective of this paper: to illustrate specific relations among product characteristics and flexibility so that careful consideration of these factors may considered or traded-off in design.

A supporting goal of this paper is to derive a set of guidelines to direct product architecture to a desired state of flexibility. Given knowledge of the physical factors that correlate with flexibility, the future objective of this research is to develop a metric for product flexibility such that a designer may evaluate the flexibility of a product by measuring a specified set of factors. This metric can be thought of as a generic measure of product flexibility since the measure does not reflect product flexibility with respect to a particular change. Of course, the bottom line is to facilitate the design of products to be flexible to future changes.

2.0 BACKGROUND

Product flexibility can be defined as degree of responsiveness (or adaptability) for any future change in a product design. This definition is consistent with Sethi's (1990) definition of product flexibility. He defines it as the ease with which the part mix currently being produced can be changed inexpensively and rapidly. Concern about flexibility is certainly not new. It has arisen in numerous economic and organizational contexts in the last 70 years (Sethi & Sethi, 1990). Product flexibility allows a company to be responsive to the market by enabling it to bring newly designed products quickly to the market (Carter, 1986). Since the future product designs are usually unknown; it becomes important to design and develop the product architecture to be flexible. According to Hayes and Schmenner (1978), smaller companies in many industries often adopt a strategy of competing on the basis of product flexibility, i.e., their ability to handle difficult, nonstandard orders and to lead in new product introduction. It should be noted that Tombak (1988) in an extensive econometric study finds that product flexibility is more important in the growth phase of a product. Because of the importance of product flexibility in the product evolution process, this paper seeks to present a better understanding of product flexibility in terms of physical factors in design.

3.0 METHODOLOGY

This research includes three major components:

(1) An extensive empirical study to measure different physical characteristics in a product across a sample set of products. These factors are identified based on their direct or indirect influence on flexibility.

(2) Evaluate the flexibility using Change Modes and Effects Analysis (CMEA), a questionnaire-based method to access the redesign "cost" for a set of possible-future changes in a present design (Palani, et al., 2003).

(3) After the products are rated for flexibility using CMEA, the fundamentals of product flexibility are investigated by plotting the flexibility ratings versus various physical characteristics. These plots are then analyzed in term of overall trends and phenomena in local regions.

Measuring Physical Factors

The following section explains how we performed the measurement for various physical factors. Based on our previous research and interviews with product designers (Palani, et al., 2003), we choose to measure the following factors: parts, functions, modules, interfaces, type of interfaces (inter-modular or intra-modular interfaces), and number of OEM (original equipment manufacturers) parts. This set of factors creates a foundation for this and future studies. Other factors may be considered in focused investigations for particular industry sectors or technologies.

For the products factors of our study, consider the following definitions:

Parts: The number of parts or components in a product is documented from the bill of materials after the disassembly of the entire product under study.

Functions: In order to consistently count the number of functions in a product, the functional models of these products are developed using the functional basis and methodology reported in (Otto & Wood, 2001). A functional model is a description of a product or process in terms of the elementary functions that are required to achieve its overall function or purpose. Customer needs are the basis for these functional models.

Interfaces and Modules: An interface in a product is defined as "a spatial region where energy, material, and/or information flow between components or between a component and the external environment" (VanWie, 2000). To document the interface data, we use a component-component style matrix called the Design Structure Matrix (DSM). This matrix is useful because it facilitates a complete view of the product configuration in a reasonably concise format (Sosa, et al. 2000). Using the same DSM representation, a consistent method for identifying assembly modules is used for all products. A set of parts is considered an assembly module if the set of parts could be assembled in parallel with the assembly of the rest of the product. An illustration of this data collection process is explained with a Dustbuster Cordless Vacuum (B&D) DB250C in Section 4.0 of this paper.

Background on Change Mode and Effects Analysis (CMEA)

Our initial efforts to understand product flexibility involved developing quantitative tools to evaluate products for flexibility. Based on the complexity of this problem (assessing product flexibility), and from our initial observations and interviews for consumer products on the market, we decided to research well known questionnaire-based methodologies used in industries to solve analogous problems. An established industry method, known as Failure Mode & Effects Analysis (FMEA), 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, to protect consumers, and to proactively avoid potential product liabilities. In FMEA, a manufacturing system or a design is evaluated for possible failures. Instead of evaluating the failure modes, as in FMEA, we propose to evaluate possible future changes in a product. This concept, referred to as Change Mode & Effects Analysis (CMEA), is explained as follows:

The preliminary step in this process is to decompose a product in a rational and systematic manner so that it can be assessed for possible changes. This assessment calls for predictive customer needs analysis and the futuristic generation of design changes/concepts. Depending on the complexity of the product under study, this decomposition can be completed with respect to functions, parts or modules. The second step in this method is to assess the 'Change Potential Number' (CPN) for a product for possible future 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. This rating is analogous to the 'Risk Priority Number' (RPN) in FMEA.

In order to assess the overall flexibility (CPN) in CMEA, each product is evaluated based on three factors, namely

1. *<u>Design flexibility (F)</u>:* The extent to which a particular change will affect the entire product in terms of redesign.
2. *<u>Occurrence (O):</u>* The probability of occurrence of this particular change in this product. The probability of occurrence can be determined based on the rate of occurrence of these particular changes. These changes can be broadly categorized as: Drawback or opportunities in the present design and time dependent change. Here the time dependent changes include the technology change over time, the company's future plans in the evolution of this product and future expectations from their customers on the performance envelope of these products.
3. *<u>Readiness (R):</u>* The capability of the company to be ready for that particular change. Readiness is based on factors such as manufacturing flexibility, supply chain flexibility, organizational flexibility and financial readiness of a company to react to a change or redesign.

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, and R is Readiness.
N = the maximum of (number of potential effects of change, number of potential causes of changes).

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. Based on this formulae (Eqn. (1)), a completely flexible product is a one in which the redesign cost incurred is minimal for any future change in the design.

Evaluating the products with all three factors, design flexibility (*F*), occurrence (*O*) and readiness (*R*), requires significant internal and confidential data from associated companies. In the absence of information of a company's manufacturing facility, supply chain facility, organizational flexibility and operational flexibility, it is difficult to access the 'readiness' of a company for a particular change in their product design. Similarly, accessing the 'occurrence' of a particular change requires rigorous customer reviews and opinions of experienced designers in that product segment. Based on these issues, we choose to validate this method, for this initial study, using design flexibility (*F*). Equation (1) is then reduced to:

$$Design\_Flexibilty = \frac{1}{10\times N}\sum_{i=1}^{N}Fi \qquad (2)$$

An illustration of how CMEA is used to evaluate the design flexibility (F) of a Dustbuster Cordless Vacuum is discussed in following section. After the products are rated on design flexibility (*F*), they are compared with the physical factors measured in the first part of this empirical study by plotting the design flexibility (*F*) of the products versus the various parameters.

4.0 EMPIRICAL STUDY EXAMPLE AND METHOD

Consumer products are selected as the data set because they represent a significant aspect of design focus in industry (McAdams, et al., 1998). Additionally these types of items are readily available and lend themselves to disassemble and physical study. One of the products in this study is the Black & Decker Dust Buster Cordless vacuum cleaner. We now discuss the complete data collection procedure of this product to show how the investigation of factors affecting product flexibility is executed.

Figure 1. Dustbuster Cordless Vacuum (B&D) DB250C

<u>Measuring physical factors</u>

<u>Functions:</u> The procedure begins with functionally decomposing the product using functional models. The functional information detailing all possible functions performed by the product is obtained from the function models (Otto & Wood, 2001). A functional model is a description of a product or process in terms of the elementary functions that are required to achieve its overall function or purpose. Customer needs are the basis for these functional models. One important aspect to be followed throughout the study is the granularity of these functional models. The same level of granularity must be maintained throughout the study for accurate and consistent comparisons. In order to maintain the granularity of these functional models, the customer needs are ranked over a scale of 1 to 5 (as shown in part in Table 1) based on their importance and the number of times they occurred during the customer reviews (conjoint analysis). The customer needs, which are rated greater than or equal to 3 are taken into consideration for constructing the functional models

of the products, where ‘3’ means that the customer when making a purchasing decision considers these aspects or features as important and ‘5’ means it is a must (critical).

Table 1. Partial Customer needs analysis of B&D Vacuum

Customer Need	Scaled Customer Need Rating (1 to 5)
Cleans debris well.	5
Has large capacity to hold debris.	4.2
Does not make noise.	2.4
Is Lightweight?	3
Is ergonomic to handle.	3.8
Has long power cord.	4
Has the ability to store power.	3
Is rugged.	3.2
Does not heat up quick.	3
Debris is easy to dispose.	3.6
Is available in attractive colors.	3

The functional model for the B&D Cordless Vacuum is shown in Figure 2. Notice that the functional model focused on the execution phase of the product related to the customer needs in Table 1. At least one function, or chain of functions, is directly related to each customer need. Once this functional model is derived, the total number of functions in a product is found by simply counting the number of boxes in the functional model. Similarly the number of functional modules is also recorded. The basis for identifying these modules are based on systematic module heuristics found in Otto & Wood, 2001. Separate functions or a group of functions that can be clearly identified as an assembly module are identified as a functional module in this empirical study. These function modules are denoted by dotted lines in Figure 2. For example in this functional model in Figure 2, “convert EE to ME” is a functional module as well as an assembly module (motor). Similarly the “Import EE and change EE” together form a functional module since they can be identified as a separate assembly module namely the “adaptor”.

Interfaces and Modules: The number of parts is counted after disassembling the product and creating a list of components in the product. Following this step, a DSM style structure is created for each product in order to document the partitioning of assembly modules and components. A consistent method for identifying the number of assembly modules, physical interfaces, and inter-modular physical interfaces is used for all products (VanWie, 2001). The documentation of this physical structure for a Cordless Vacuum is given in Figure 3. The interfaces are identified by marking a “1” whenever two components possess an interface. Similarly inter-modular interface is identified as an interface between one or more modules. A tree structure of the assembly modules and components is derived from the DSM so that the hierarchy of parts is clear. This tree structure allows one to easily count the number of branches between assemblies and components.

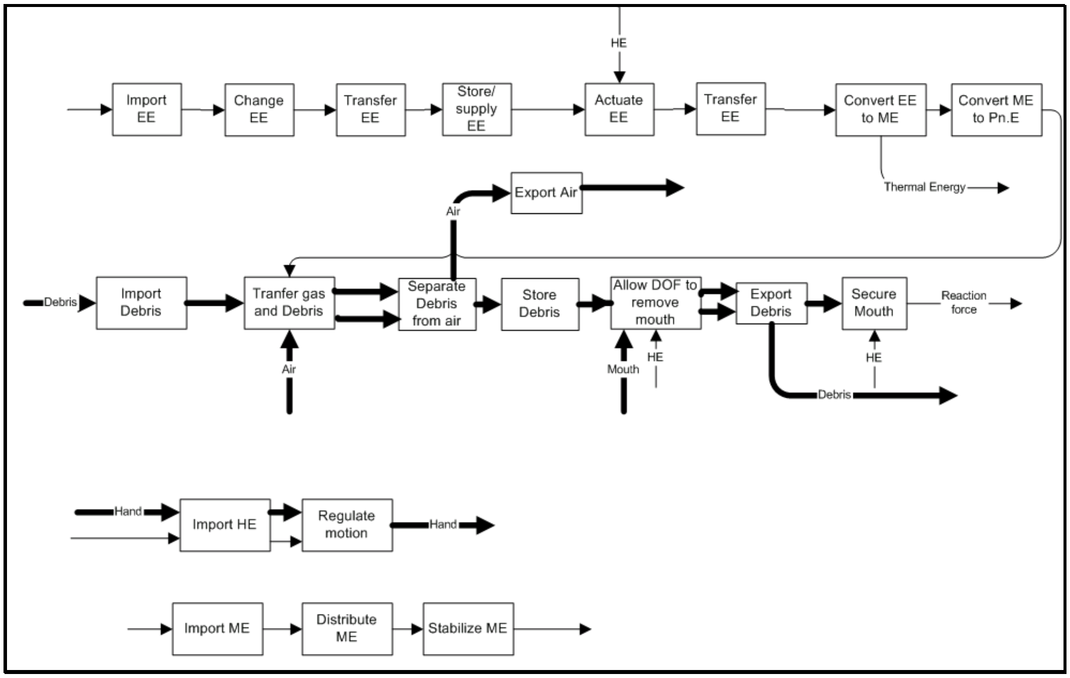
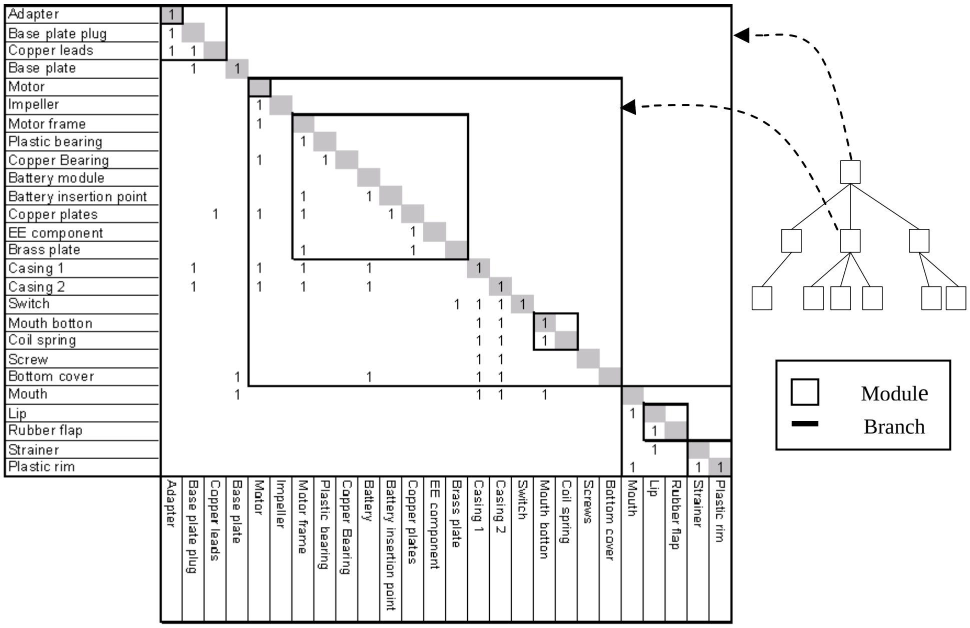


Figure 2. Functional Model of B&D Cordless Vacuum



	Adapter	Base plate plug	Copper leads	Base plate	Motor	Impeller	Motor frame	Plastic bearing	Copper Bearing	Battery	Battery insertion point	Copper plates	EE component	Brass plate	Casing 1	Casing 2	Switch	Mouth botton	Coil spring	Screws	Bottom cover	Mouth	Lip	Rubber flap	Strainer	Plastic rim
Adapter	1																									
Base plate plug	1																									
Copper leads	1	1																								
Base plate		1		1																						
Motor																										
Impeller					1																					
Motor frame					1																					
Plastic bearing							1																			
Copper Bearing					1			1																		
Battery module																										
Battery insertion point							1			1																
Copper plates			1		1		1				1															
EE component												1														
Brass plate							1					1														
Casing 1		1			1		1			1					1											
Casing 2		1			1		1			1						1										
Switch														1	1	1	1									
Mouth botton															1	1		1								
Coil spring															1	1		1								
Screw															1	1										
Bottom cover				1						1					1	1										
Mouth				1											1	1		1								
Lip																						1				
Rubber flap																							1			
Strainer																							1			
Plastic rim																						1			1	1

Figure 3. Physical assemblies, components, and interfaces of a B&D Cordless Vacuum

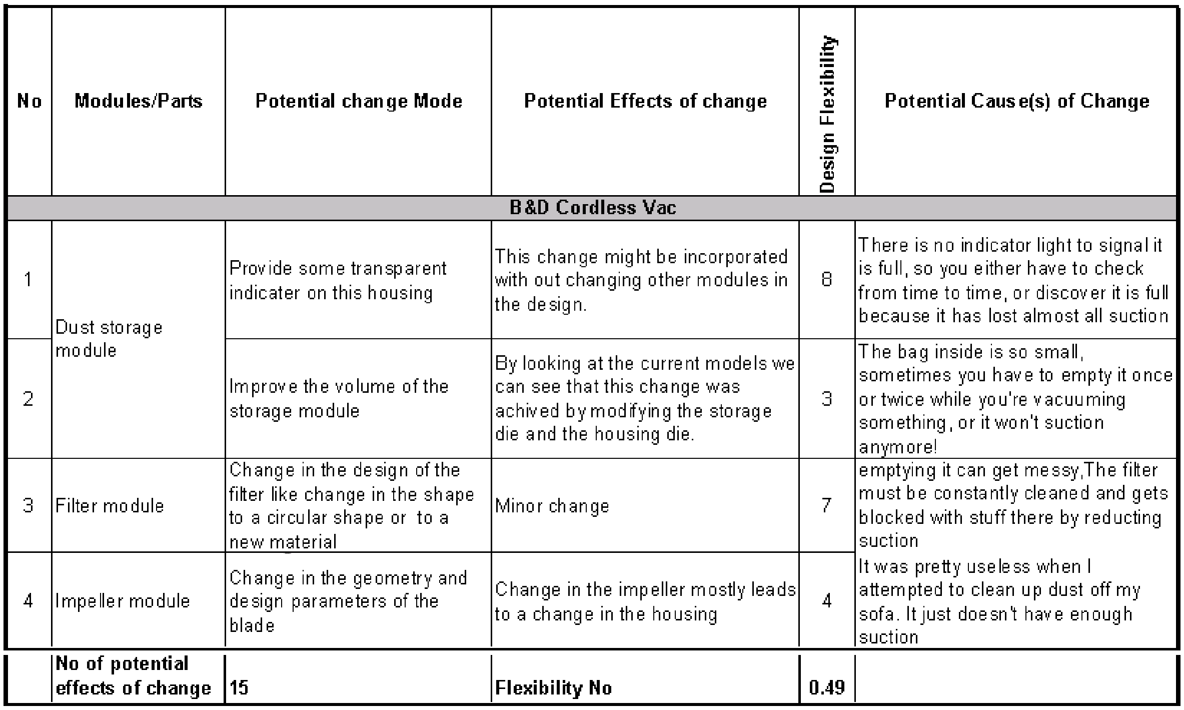
Assessing design flexibility (F)

The Change Modes and Effects Analysis for this Dustbuster vacuum cleaner is shown in Table 3. The first step in this process is to gather the customer needs by studying extensive reviews from data sources (websites like. www.amazon.com, www.epinions.com, warranty information etc.). 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' does 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 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 Dustbuster Cordless Vacuum example in Table 3, consider the 'Dust storage module' (Figure 16) where the 'Potential change mode' is 'Provide transparent indicator on the housing.' and 'Potential Effect of change' is 'this change can be incorporated without changing other modules in the design.' The housing used in the dust storage module can be made transparent by changing the type of material used during the molding process. This can be observed in the next generation of this Dustbuster in the market. Hence this change is indicated as a 'Minor Redesign' according to Table 2.

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 that involves almost no cost incurred.	9
None	No effect	10

Table 3. Partial CMEA on Dustbuster cordless vacuum.



No	Modules/Parts	Potential change Mode	Potential Effects of change	Design Flexibility	Potential Cause(s) of Change
B&D Cordless Vac					
1	Dust storage module	Provide some transparent indicater on this housing	This change might be incorporated with out changing other modules in the design.	8	There is no indicator light to signal it is full, so you either have to check from time to time, or discover it is full because it has lost almost all suction
2		Improve the volume of the storage module	By looking at the current models we can see that this change was achived by modifying the storage die and the housing die.	3	The bag inside is so small, sometimes you have to empty it once or twice while you're vacuuming something, or it won't suction anymore!
3	Filter module	Change in the design of the filter like change in the shape to a circular shape or to a new material	Minor change	7	emptying it can get messy,The filter must be constantly cleaned and gets blocked with stuff there by reducting suction
4	Impeller module	Change in the geometry and design parameters of the blade	Change in the impeller mostly leads to a change in the housing	4	It was pretty useless when I attempted to clean up dust off my sofa. It just doesn't have enough suction
	No of potential effects of change	**15**	**Flexibility No**	**0.49**	

5.0 RESULTS AND DISCUSSION

The products in this study include seventeen consumer devices that range in domain from small scale to medium scale consumer products (e.g. manual screwdriver, hand blender, power tools, etc.). The results are summarized in Table 4 and arranged in a series of graphs that illustrate the relationships among the factors evaluated in this study. In the following discussion, the references to “modules”, “interfaces”, and “functions” correspond to the definitions described above. The CMEA analysis is done on these 17 products and their design flexibility (*F*) ranking is listed in Table 4. Several interpretations are taken from the graphs from the perspective of both overall trends and phenomena in local regions. The goodness of fit i.e. the R^2 values for these trends are denoted in each of these graphs to show how strongly physical factors correlate with flexibility.

Figures 4, 5 and 6 show an overall strong correlation between number of parts, functions and interfaces with design flexibility (*F*). From these graphs we observe that as the number of parts, functions and interfaces in a product increases the design flexibility (*F*) increases. Figure 7 show that there is a strong correlation between the number of modules and design flexibility (F). This graph strongly suggests that design flexibility (F) is directly proportional to the number of modules in the product; hence making a design more modular reduces the redesign cost for any future change. When observing the Figures 4,5,6 and 7 the overall trend suggests that as a device is effectively partitioned into a greater number of elements (manifested through higher numbers of components and functions), the flexibility increases. This is logical since an increase in partitioning would seem to lessen the impact of any individual element on the whole if a change becomes necessary for the element in question.

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Conversely in Figure 8, the ratio of number of functions to parts is inversely proportional to the design flexibility (*F*). The weak overall trend in this suggests that as the design is more integrated, it offers more resistance to a change in terms of redesign cost. This is rational because when many functions are shared in few components in a product, and if a future change occurs in any one of these functions, the entire product has to be redesigned.

Table 4. Summary of results from the empirical study

Product	Number of parts	Number of Functions	Number of Assembly modules	Number of functional modules	Number of Interfaces	Number of inter-modular interfaces	Number of OEM parts	Number of inter-modular interfaces / interfaces	Number of functions/parts	Design Flexibility (*F*)
5 in 1 power handy kit	61	31	16	12	125	60	11	0.48	0.47	0.53
Braun multipurpose hand blender	64	29	18	8	102	35	7	0.34	0.45	0.52
B&D jig saw	60	28	13	9	117	51	21	0.44	0.37	0.51
Dustbuster B&D	27	21	9	7	66	34	4	0.52	0.68	0.49
Craftsman 3/8 in Drill	47	24	11	7	66	21	11	0.32	0.41	0.48
Handiwork Screw driver	42	18	12	6	81	45	18	0.56	0.38	0.44
Dirt Devil spot scrubber	58	31	14	8	122	54	9	0.44	0.40	0.44
B&D Electrical Knife	33	21	6	5	60	26	5	0.43	0.51	0.44
Paper-mate Multi-pen	28	19	9	5	55	18	3	0.33	0.68	0.39
Presto salad shooter	29	18	7	4	46	14	5	0.30	0.51	0.37
Multi Bit Manual screwdriver	10	9	2	1	23	7	0	0.30	0.90	0.32
Coleman Quick pump	21	15	6	4	42	15	0	0.36	0.58	0.30
Braun coffee grinder	12	12	5	3	22	10	1	0.45	0.86	0.27
Arrow light duty stapler	15	13	2	2	37	7	1	0.19	0.68	0.19
Disposable pen	5	4	2	1	10	4	0	0.40	0.80	0.17
Stanley Screw driver	2	5	0	0	3	0	0	0.00	2.50	0.15
OXO Good Grips Knives	2	3	0	0	3	0	0	0.00	1.50	0.13

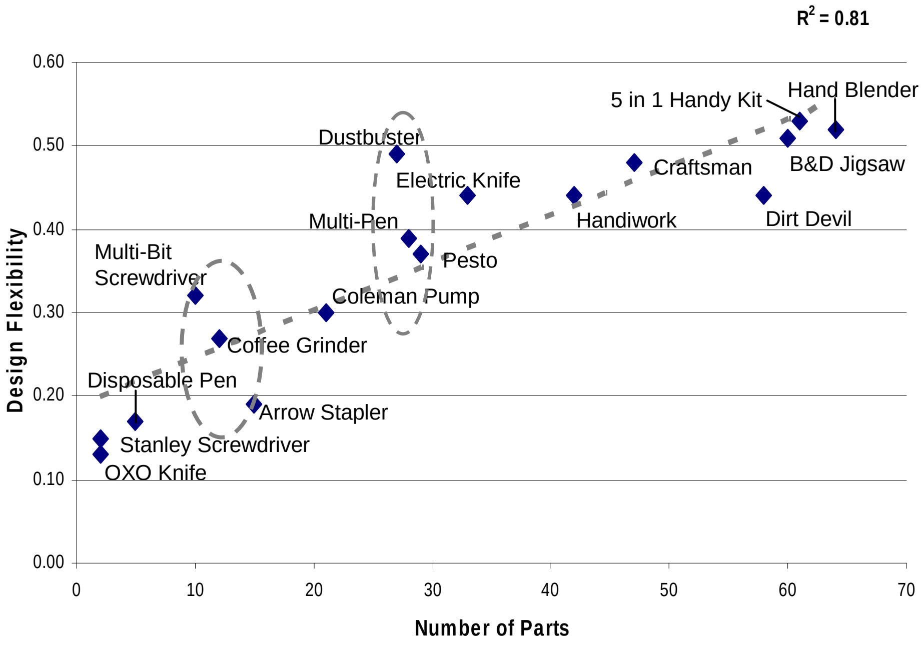

Figure 4. Design Flexibility vs Number of Parts

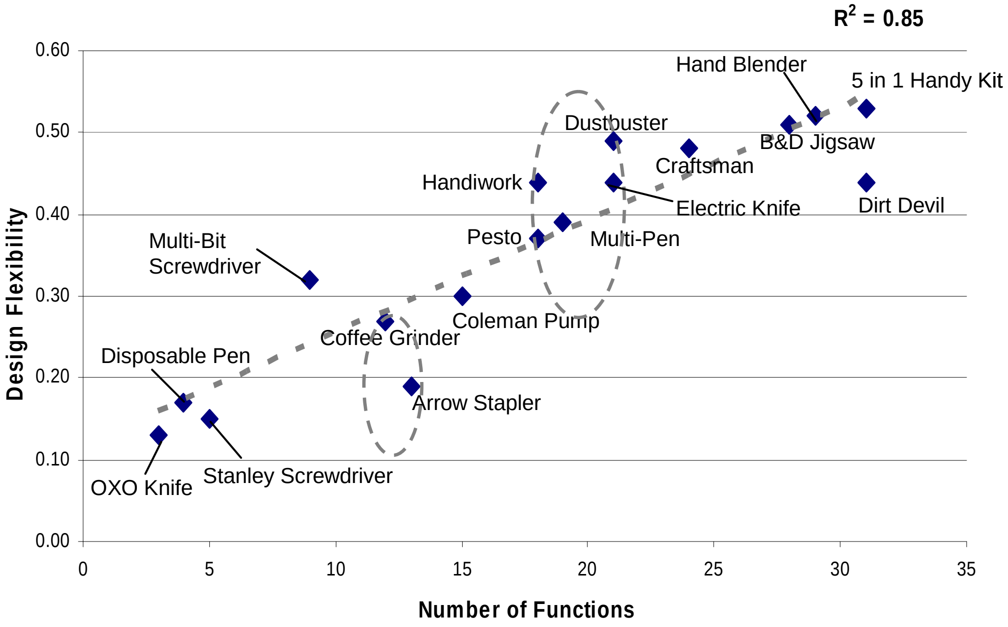

Figure 5. Design Flexibility vs Number of Functions

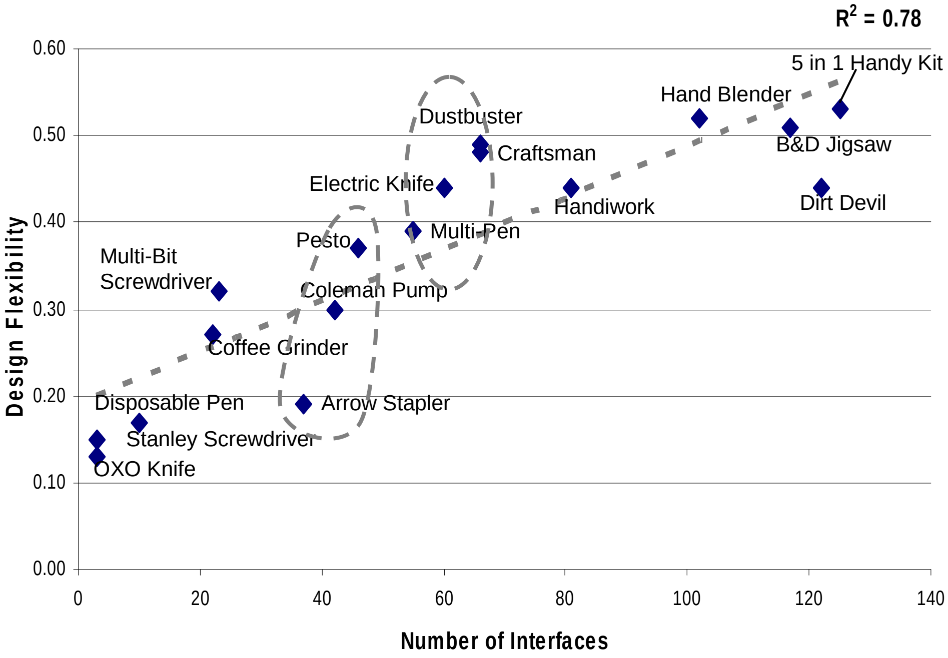

Figure 6. Design Flexibility vs Number of Interfaces

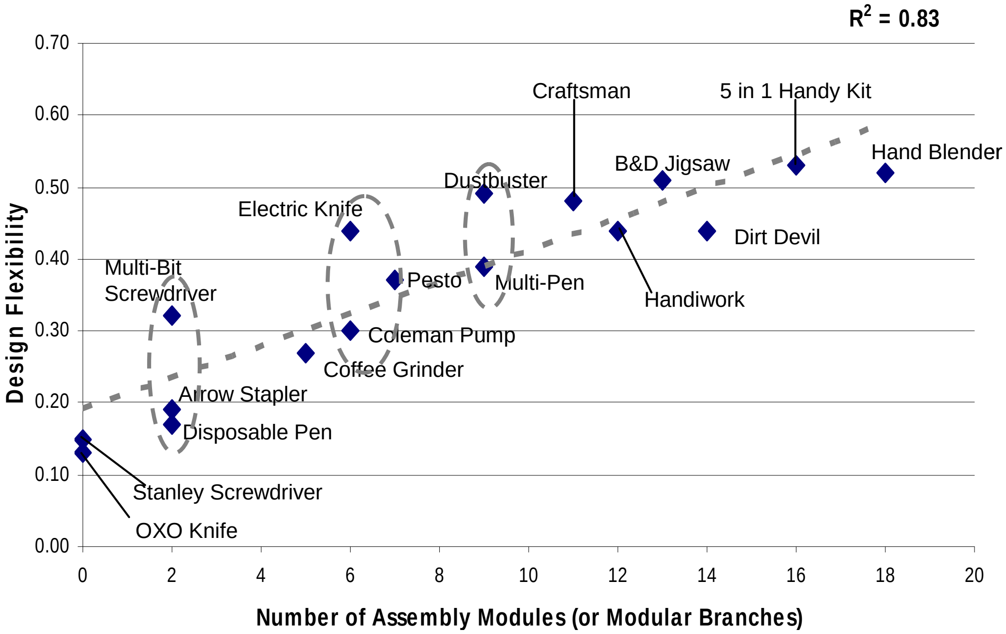

Figure 7. Design Flexibility vs Number of Assembly Modules

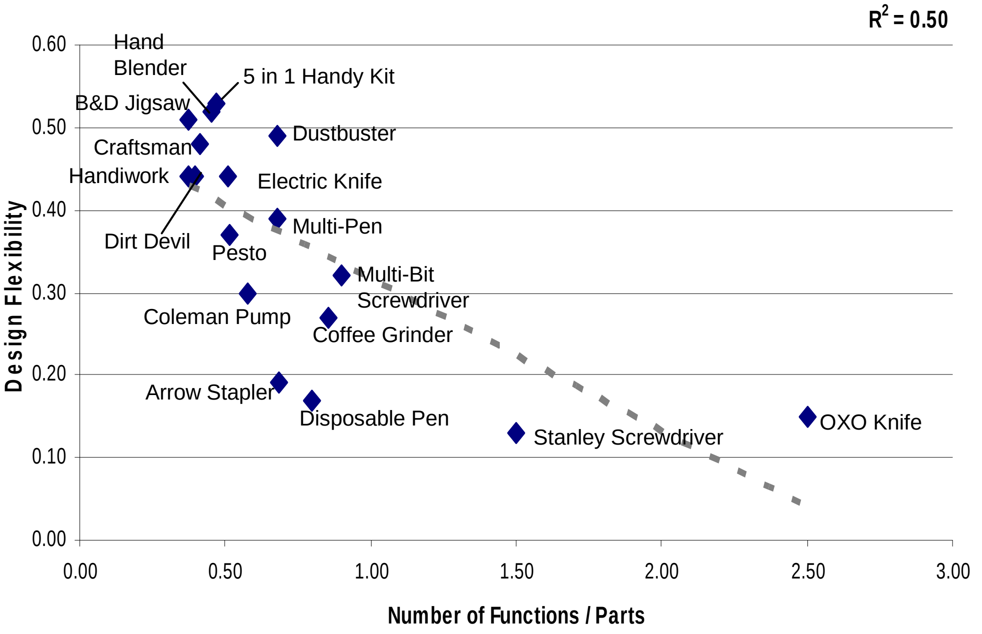

Figure 8. Design Flexibility vs Number of Functions / Parts

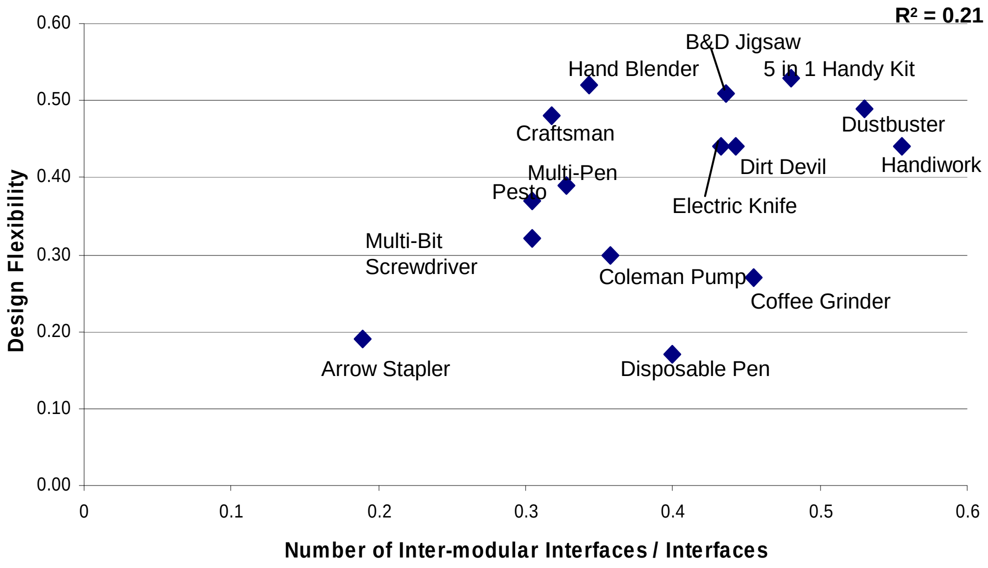

Figure 9. Design Flexibility vs Number of Inter-Modular Interfaces / Interfaces

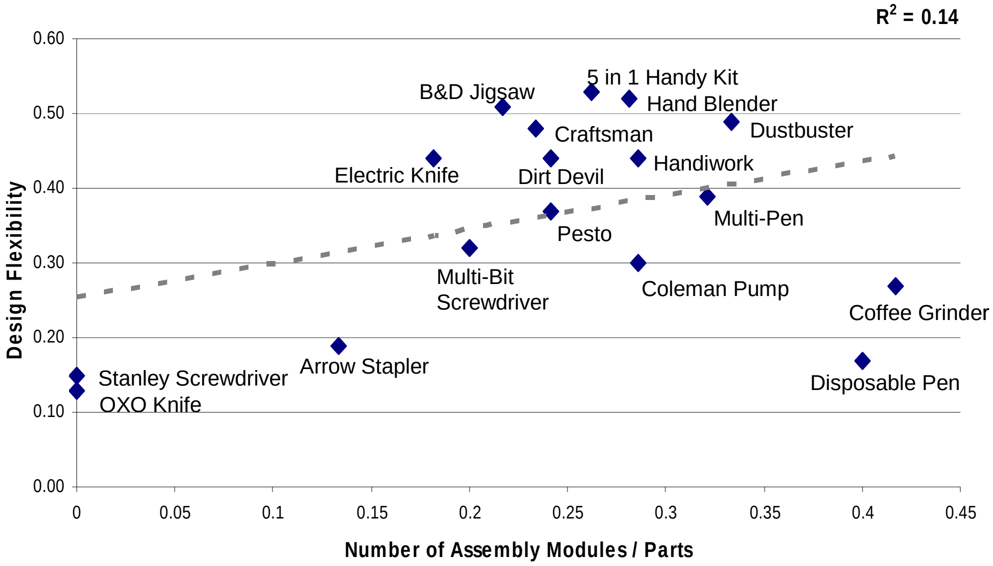

Figure 10. Design Flexibility vs Assembly Modules / Parts

In order to investigate the issue of how the modules interact in the design we plotted the ratio of number of inter-modular interfaces to total interfaces with Design Flexibility. We found in Figure 9, that though the data form a sparse pattern there is a very weak overall trend showing that as the ratio of inter-modular interfaces to interfaces increases the design flexibility (F) increases. However conclusive insights cannot be obtained from this graph.

Figure 10, is a plot between ratio of number of assembly modules to parts with flexibility. One can observe that the data is a sparse pattern with no clear overall trend. It appears that the degree of part aggregation per part (modules / part) does not affect flexibility. This assumes that the notion of modularity is equivalent to the lumping of components. This suggests that flexibility is independent of the number of parts in a module. This is an important finding because this suggests the designer that increasing or decreasing the number of parts in a module does not affect flexibility. This is intuitively reasonable since aggregation is sort of the opposite of partitioning and so the effects seem to cancel out. On the surface it may seem to contradict Figure 4, which shows that reduced number of overall parts will lead to a reduction in flexibility. But the reader should carefully note that Figure 10 suggests that, the flexibility is independent of the number of parts in a module. Therefore, the number of parts can be reduced in each module, which in turn leads to reduction in the assembly cost. This implies that we can design for assembly while maintaining the flexibility.

Now referring again to Figures 4,5 and 6 we observe roughly horizontal regions where significant differences exist in the design flexibility (F) rating while little differences exists in the number of parts, functions and interfaces. These highlighted regions contain a reasonable group of products. In these areas clearly something besides part count, interfaces and functionality is affecting the flexibility of a product design. When observing Figure 7 with respect to these horizontal regions we found that these products did not have significant difference in the number of modules. For example in Figures 4, 5 and 6 consider the horizontal region, which consists of the Dustbuster, Electric knife, Papermate Multi-pen and Pesto salad shooter. In this case we can see that the Dustbuster is more flexible when compared to the Multi-pen even though both had the same number of parts, interfaces and functions. Similarly when observing Figure 7, we can see that the Dustbuster has the same number of modules as the Multi-pen. This leads us to an interesting insight, where even though in a broader perspective the flexibility of a design is driven by the number of parts, functions, interfaces and modules there is something about the way these modules are arranged in the design that makes the design more flexible. This issue can be explained with help of Figure 9, which is a plot between the ratio of number of inter-modular interfaces to interfaces with design flexibility (F). When we observe the Dustbuster and Multi-pen, the former has greater number of inter-modular interfaces when compared to the later. Similar results can be observed with other groups of products, which are highlighted in Figures 4, 5, 6 & 7.

However based on observations of DSM and physical products, it appears that most of these modules in more flexible products (Dust buster, B&D electric knife & multi-bit screwdriver) are external attachments. Alternatively most of the modules in the less flexible products (Arrow stapler, Coleman pump & Papermate Multi-pen) are enclosed inside the housing. This can be observed in Figures 11 & 12 where the Dustbuster is more flexible and has more number of external modular attachments when compared to Paper-mate Multi-pen.

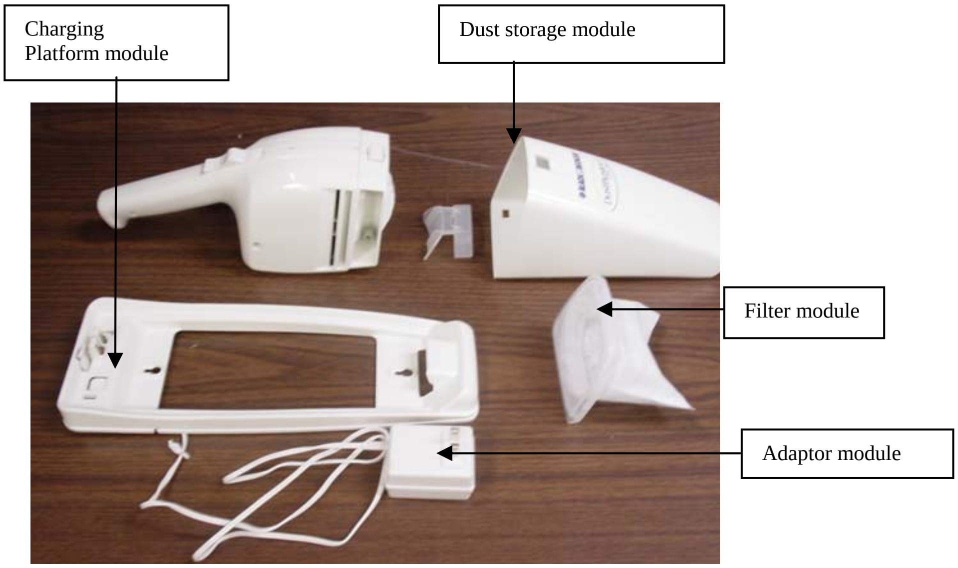

Figure 11. Dustbuster Cordless Vacuum (B&D) DB250C

Figure 12. Paper-mate Multi-pen

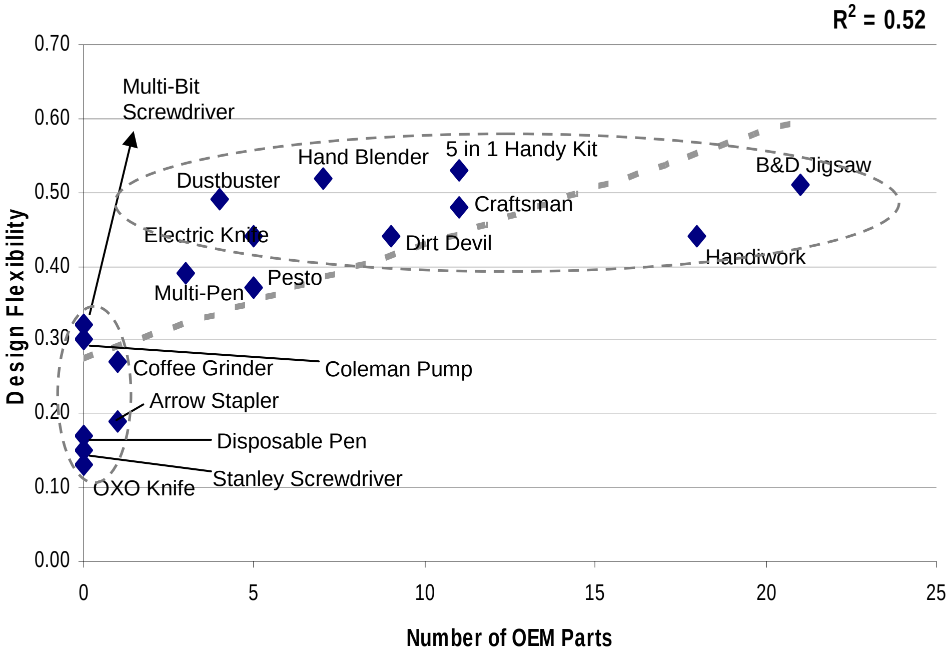

Figure 13. Design Flexibility vs Number of OEM parts

Figure 13, shows a weak overall trend that suggests the number of OEM parts is directly proportional to design flexibility (F). In this figure one can notice two groups of data, which are highlighted. The group that has less design flexibility (F) had no OEM's when compared to the other one. This trend makes sense because changing an OEM component would likely require less effort than the redesign and retooling for a custom fabricated part. Typical OEM components included in this study are such things as standard DC motors, switches, etc.

In the same graph one can observe that although the Handiwork screwdriver and the B&D Jigsaw had large number of OEM parts they did not have a proportional increase in their flexibility. When observing these physical products, and during the Change Mode and Effects Analysis it was found that most of these OEM part or modules were enclosed inside the housing of the product. Therefore, whenever a change is imposed on these OEM parts, because of the geometric dependency, the housing also had to be changed. This again supports the insight, having the modules, as external attachments will reduce the effect of a given change. Figure 17 shows the group of OEM parts and modules (motor, batteries, switch assembly, etc.) enclosed inside the Handiwork screwdriver housing.

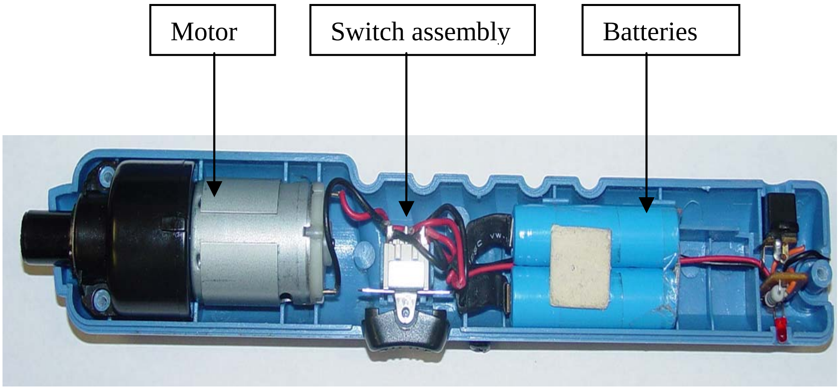

Figure 14. Handiwork Screwdriver with housing removed

When trying to understand the nature of products chosen for this empirical study, the parameters in the products such as number of functions, number of interfaces and number of assembly modules were plotted with respect to the number of parts. Figure 15, 16 and 17 show the correlation between the physical parameters like number of parts, functions, modules, and interfaces. We can observe a strong correlation between them. The general trend in Figure 15 shows the increase in part count to achieve the added functionality in the products. Figure 16 and 17 are consistent with VanWie's(2000) empirical results. In Figure 17 the general trend suggests the implementation of modular strategy for the increasing part count. These graphs remind us of the importance of determining the interdependence of these physical parameters when developing a quantitative metric to measure flexibility. What might be interesting is to study products where the number of parts is not directly proportional to the number of functions or modules or interfaces. Including these products will make this study more interesting by adding more variances to the graphs.

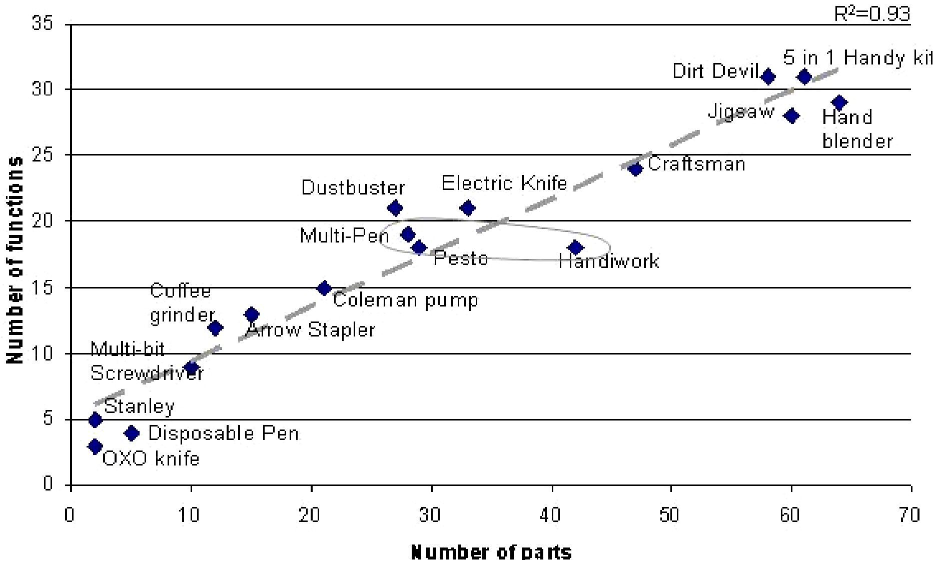

Figure 15. Number of Functions vs Number of Parts

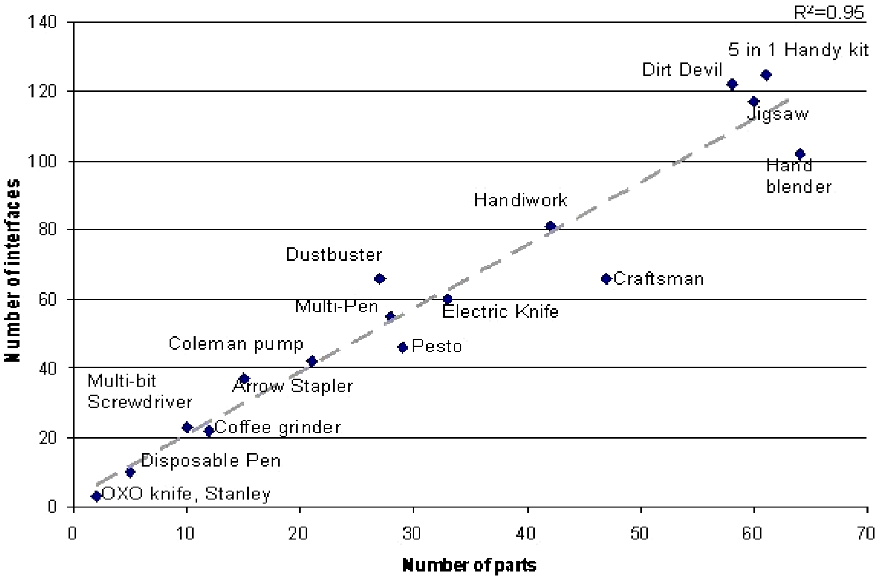

Figure 16. Number of Interfaces vs Number of Parts

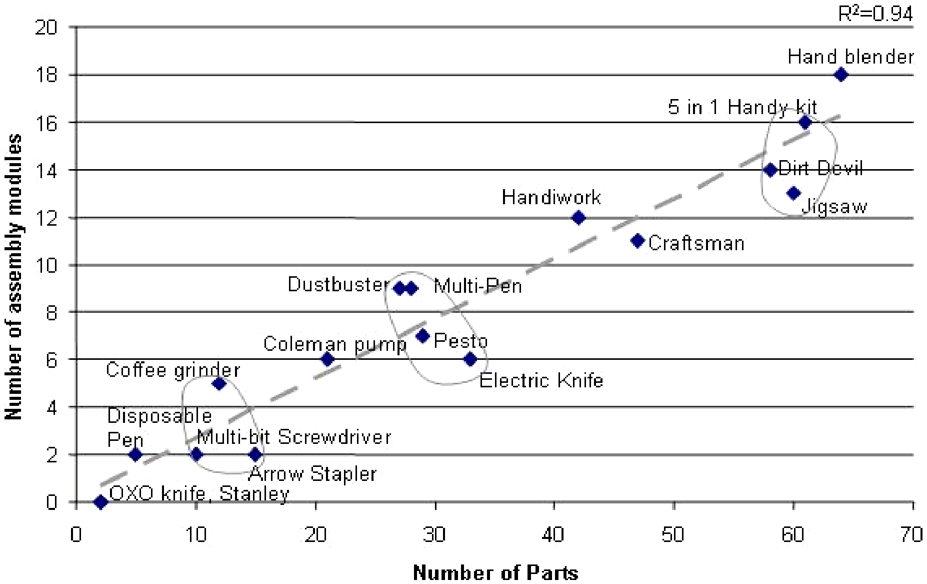

Figure 17. Number of Assembly Modules vs Number of Parts

6.0 CONCLUSIONS AND FUTURE WORK

The overall objective of this paper is to understand the various physical factors that correlate with product flexibility. We show through an empirical evaluation of seventeen products that product flexibility is affected by physical factors such as number of parts, functions, interfaces, type of interfaces, modules and the way these modules are designed in the product. The insights obtained during this study are summarized as follows:

1. *Modularizing the design leads to more product flexibility. As the design becomes more integrated it becomes more inflexible for redesign.*
2. *Designing the modules in a product as external attachments makes the design even more flexible.*
3. *Designing with more standard components and interfaces will improve product flexibility.*
4. *Directed partitioning of a design into a greater number of elements (manifested through higher numbers of components and functions) improves the flexibility.*
5. *Reducing the number of parts within modules after effective layout does not affect flexibility (this insight must be verified in future studies). The implication is the simultaneous design for improved assemblability while maintaining flexibility.*

With help of these insights, the designer can exercise and focus their efforts to control the flexibility of a design. The information in this paper is a significant step toward collecting data on how certain products are designed more flexible than others. Though time consuming, this empirical study is a productive approach towards understanding the flexibility issues in design. However one main question remain for future work, how can these physical factors be used to derived a generic flexibility metric?

REFERENCES

Benjamin S. B., and Wolter J. F., “Systems Engineering And Analysis” Prentice Hall International Series in Industrial and Systems Engineering.

Blessing, L.T.M., Chakrabarthi, A. & Wallace, K.M. 1998 “An Overview of Descriptive Studies in Relation to a General Design Research Methodology”. *In Designers: The key to Successful Product Development, Springer-Verlag, New York.*

Boothroyd, G. and P. Dewhurst, 1984. “Design for Assembly: Manual Assembly,” Machine Design, Penton Publishing Inc., Cleveland, OH.

Brown, J., Dubois, D., Rathmill, K., Sethi, S.P., and Stecke, K.E. “Classification of Flexible Manufacturing Systems.” *The FMS Magazine* (April 1984)

Carter, M.F. “Designing Flexibility into Automated Manufacturing Systems.” In Proceedings of the Second ORSA/*TIMS Conference on Flexible Manufacturing Systems*, K.E Stecke and R.Suri (Eds.), Elsevier, Amsterdam, The Netherlands, pp. 107-118 (1986).

Gerwin, D., “An Agenda for Research on the Flexibility of Manufacturing Processes.” *International Journal of Operations and Production Management*, Vol.7, No. 1, pp. 38-49 (1987).

Jaikumar, R. “Postindustrial Manufacturing.” *Harvard Business Review*, Vol.64, pp. 69-76 (November-December 1986

Mark V. M., & Kosuke Ishii, “Design for Variety: A Methodology for Developing Product Platform Architectures”, *ASME Design Engineering Technical Conference Proceedings*, DETC00/DTM-14021.

Mc Adams, D. A., Stone, R.B., Wood, K.L., 1998 “Understanding Product Similarity Using Customer Needs”. *ASME Design Engineering Technical Conference* Proceedings, DETC98/DTM-5660.

Otto, K. and Wood, K. 2001. Product Design – Techniques in Reverse Engineering and New Product Development. New Jersey: Prentice Hall.

Pahl, G. and Beitz, W. 1996. Engineering Design: A Systematic Approach. New York: Springer-Verlag.

Palani Rajan.P.K., Van Wie, M., Otto, K. & Wood, K. (2003), Matthew I. Campbell 2003 “Design for Flexibility – Measures and Guidelines”, *International Conference on Engineering Design*, Iced 03 Stockholm, August 19-21, 2003

Sethi, A.K., and Sethi, S.P., 1990, Flexibility in manufacturing: a survey. *International Journal of Flexible Manufacturing Systems*, 2 (4), 289-328.

Son, Y.K. and Park, C.S. “Economic Measure of Productivity, Quality and Flexibility in Advanced Manufacturing Systems.” *Journal of Manufacturing Systems*, Vol. 6, No.3, pp. 193-207 (1987)

Sosa, M. E., Eppinger, S. D., Rowles, C. M., 2000 “Designing Modular and Integrative Systems”. *ASME Design Engineering Technical Conference Proceedings*, DETC00/DTM-14571.

Stone, R.B. and K.L. Wood, Development of a Functional Basis for Design. *Journal of Mechanical Design*, 2000. 122(December): p. 359-370.

Stone, R. B., Wood, K. L., 1999 “Development of a Functional Basis for Design”. *ASME Design Engineering Technical Conference Proceedings*, DETC99/DTM-8765.

Suh, N.P., 1990 The Principles of Design, Oxford University Press, New York.

Ulrich, K. and Eppinger, S. 2000. Product Design and Development. Boston: Irwin McGraw-Hill.

Van Wie, M., Greer, J., Campbell, M., Stone, R., Wood, K., 2001 “Interfaces and Product Architecture”. *ASME Design Engineering Technical Conference Proceedings*, DETC00/DTM-21689

Van Wie, M., “Designing Product Architecture – A systematic Method”, PhD Dissertation, University of Texas at Austin, (2002).