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EMPIRICAL STUDY ON PRODUCT FLEXIBILITY

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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 reduction in redesign cost. When considering the efforts taken in the past to understand product flexibility and develop associated metrics, most of prior research focused towards the manufacturing domain rather than the product itself. In this paper we study product flexibility by finding the physical parameters that affect it by conducting an empirical study on existing products in the market. 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 this a set, guidelines are derived to improve product flexibility and design for it. This research is a significant step, which will lead us to our future objective of developing a generic metric and comparison design method.

1.0 INTRODUCTION

Product flexibility should be considered in design due to the changing nature of competition, constantly improving the performance and functionality of products and being responsive to differing customer needs. Despite this, product flexibility remains poorly understood in theory and poorly addressed in practice. Few metrics have been developed in the past to measure product flexibility. Such 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 prior focus on manufacturing. In this paper we study product flexibility from a fundamental point of view by correlating the flexibility with different physical parameters. An understanding of product flexibility is gained through empirically evaluating the flexibility of products in order to identify those parameters that directly correlate. So the main objective of this paper is to illustrate specific relations among these factors and flexibility so that careful consideration of these factors may provide guidance in design.

A supporting goal of this paper 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. Given knowledge of these factors, 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 simply measuring a specified set of parameters. 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. In this sense, the measure is general or generic. 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 than in its natural phase. Because of the importance of product flexibility in the product evolution process, this paper presents a better understanding of product flexibility in terms of physical parameters in design. Thus the reason for the study is to determine what parameters correlate with flexibility and how they can be measured. This will lead us to a better understanding of flexibility and help us in deriving guidelines which will help to create more flexible design.

3.0 METHODOLOGY

This research includes two primary components: the first component is an extensive empirical study to measure different physical parameters in a product across a sample set of products. These parameters are identified based on their direct or indirect effect on flexibility. The second part of this research is to evaluate the flexibility using Change Modes and Effects Analysis (CMEA), which is a questionnaire-based method to access the redesign cost for possible set of future changes in the present design (Palani, et al, 2003).

In our initial empirical study, the different parameters that are measured and how we performed the measurements are explained in the following section. Based on our understanding of the flexibility issue from our previous work on CMEA, we choose to measure the following parameters: parts, functions, modules, interfaces, type of interfaces (inter-modular or intra-modular interfaces), and number of OEM (original equipment manufacturers) parts. The number of parts in a product is counted after the disassembly of the entire product. In order to consistently count the number of functions in a product, the functional models (Stone, 1999) of these products are developed. 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. An interface in a product is defined as "a spatial region where energy and/or material 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. This Design Structure Matrix (DSM) 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 a DSM for this purpose is discussed in a later section, which provides an example product evaluation.

In the second part of this methodology, each product in the above empirical study is evaluated for overall flexibility using the Change Mode & Effects analysis. This method is explained in brief as follows. In this method in order to evaluate the overall flexibility (Change potential number) each product is evaluated based on three factors namely, design flexibility, occurrence and readiness. 'Design flexibility' is the extent to which a particular change will affect the entire product in terms of redesign. 'Occurrence' is the probability of occurrence of this particular change in this product. This 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, company's futuristic plans in the evolution of this product and future expectations from the customers on the performance envelope of these products. 'Readiness' is 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 this change or redesign. Comparing the products with all these three factors will require more work in terms of time and industrial interaction.

In the absence of information of a companies 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 more rigorous customer reviews and opinions of experienced designers in that product segment. Given the constraints for this empirical study we choose to evaluate the products initially with design flexibility.

An illustration of this CMEA to evaluate the design flexibility of a product is discussed in the later section. After the products are rated on 'Design flexibility', they are compared with the physical parameter measured in the first part of this empirical study by plotting the design flexibility of the products in the x- axis and the various parameters in the y-axis. These graphs are then analyzed in term of overall trends and phenomena in local regions.

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, D. A., et al, 1998). Additionally these types of items are readily available and are easy to disassemble and 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 factor affecting product flexibility is executed.

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

Step 1. Measuring physical parameters

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). The 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. They have to be maintained the same through out the study for more 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. 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 critical.

The functional model for the B&D Cordless Vacuum is shown in Figure 2. 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 function or a group of functions that can be clearly identified as an assembly module is 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".

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 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 can be derived from the DSM so that the hierarchy of parts is clear. This allows one to easily count the number of branches between assemblies and components.

Step 2. Accessing design flexibility of product architecture

The first sub-step in assessing flexibility 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, sub-assemblies. The Change Modes and Effects Analysis for this Dustbuster vacuum cleaner is shown in Table 3. The first step in this process is to generate the possible future changes that can occur in this design. Through out our study we generated these changes from the customer need analysis and extensive customer reviews from data sources (e.g. www.amazon.com, www.epinions.com). These changes included the drawbacks in the current design and possible future changes based on customer expectations. These changes are documented in the "Potential causes of change' column and arranged with respect to their related modules. After this process the potential change in the respective modules are documented in the "Potential change mode" column. Based on this change in this 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 flexibility ranking for this particular change in this design is assigned.

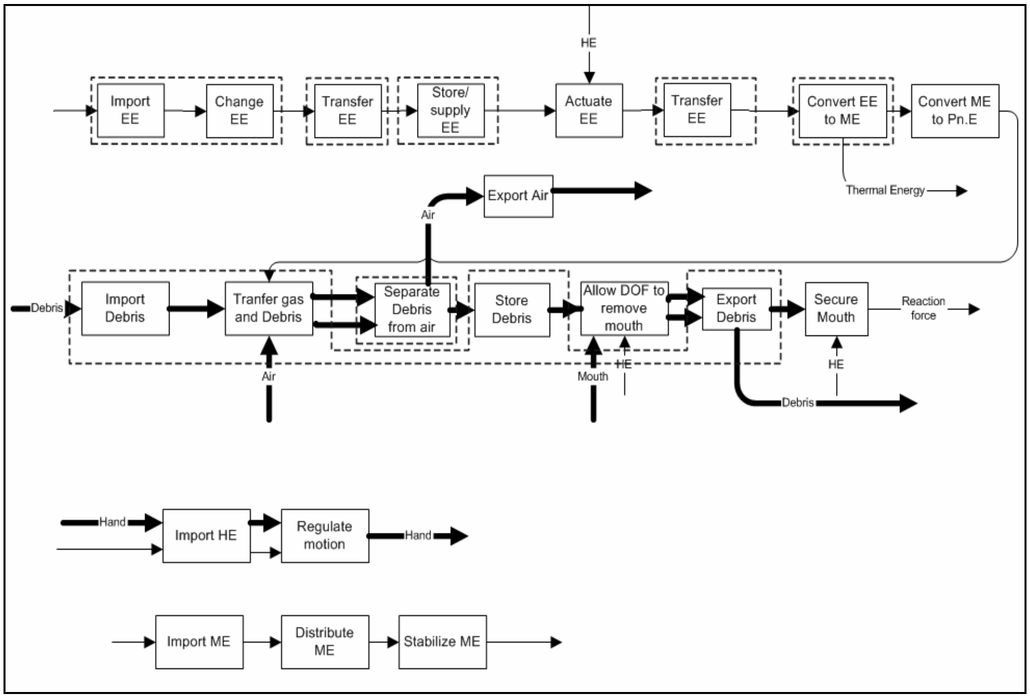

Figure 2. Functional Model of B&D Cordless Vacuum

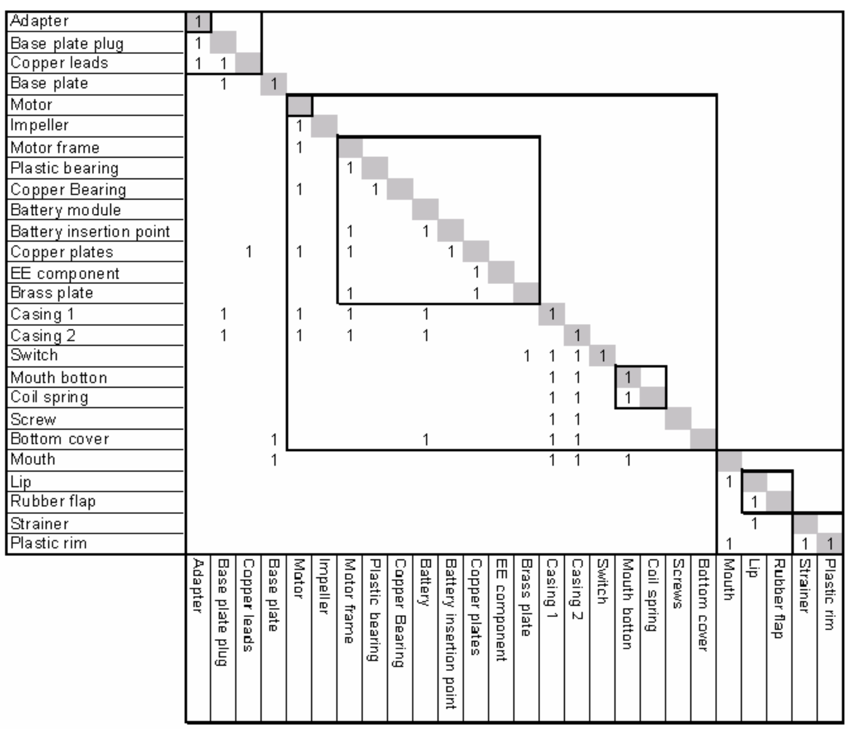

Figure 3. Physical assemblies, components, and interfaces of a B&D Cordless Vacuum

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

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 reducing 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 parameters evaluated in this study. In the following discussion, the references to “modules”, “interfaces”, and “functions” correspond to the definitions described above. 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 parameters correlate with flexibility.

Figures 4, 5 and 6 show an overall strong correlation between number of parts, functions and interfaces with design flexibility. From these graphs we observe that as the number of parts, functions and interfaces in a product increases the design flexibility increases. In Figure 7 and 8 we show that there is a strong correlation between the number of modules and design flexibility. We can clearly observe from these two graphs that design flexibility is directly proportional to the number of modules in the product. This data proves that making a design more modular reduces the redesign cost for any future change.

When observing the Figures 4,5,6,7 and 8 the overall trend show 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.

Conversely in Figure 9, the ratio of number of functions and parts is inversely proportional to the design flexibility. 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. It is quite logical 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 whole components has to be redesigned.

In order to investigate the issue of how the modules interact in the design we plotted the ratio of number of inter-modular interfaces and total interfaces with design flexibility. We found in figure 10 that though the data is a sparse pattern there is very weak overall trend showing that as the ratio of inter-modular interfaces and interfaces increases the design flexibility increases. However conclusive insights cannot be obtained from this graph.

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
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

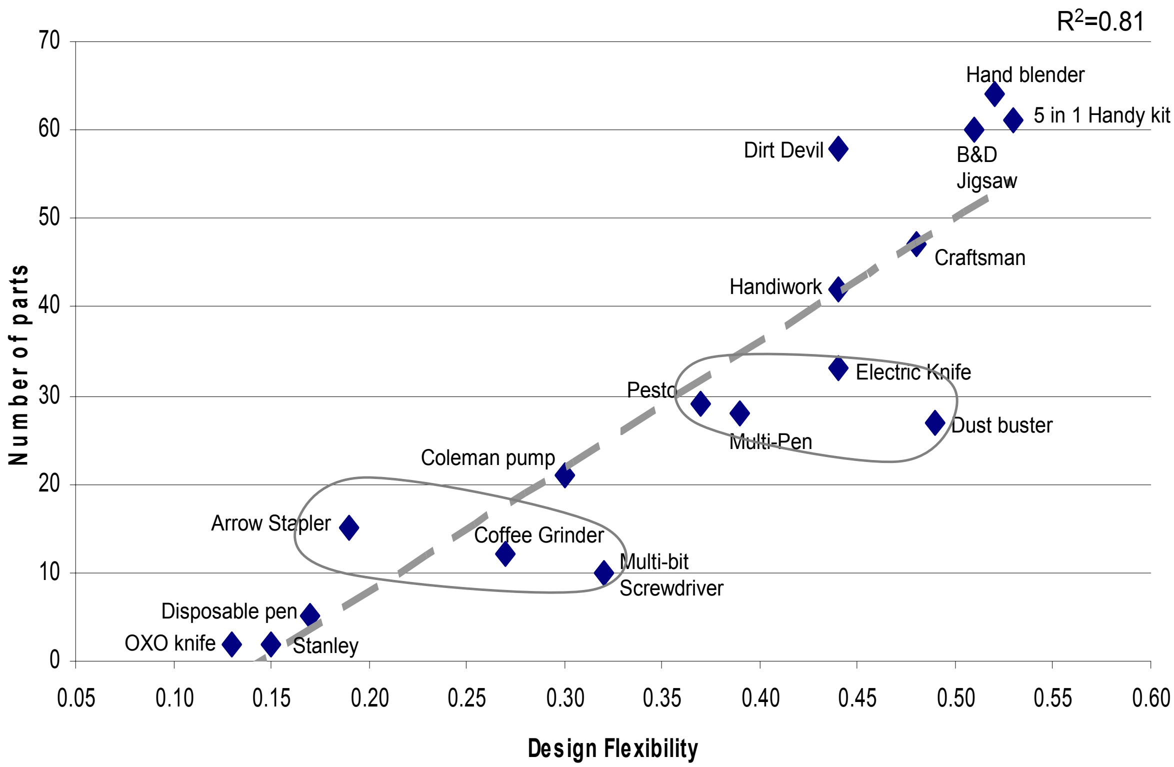

Figure 4. Design Flexibility vs. Number of parts

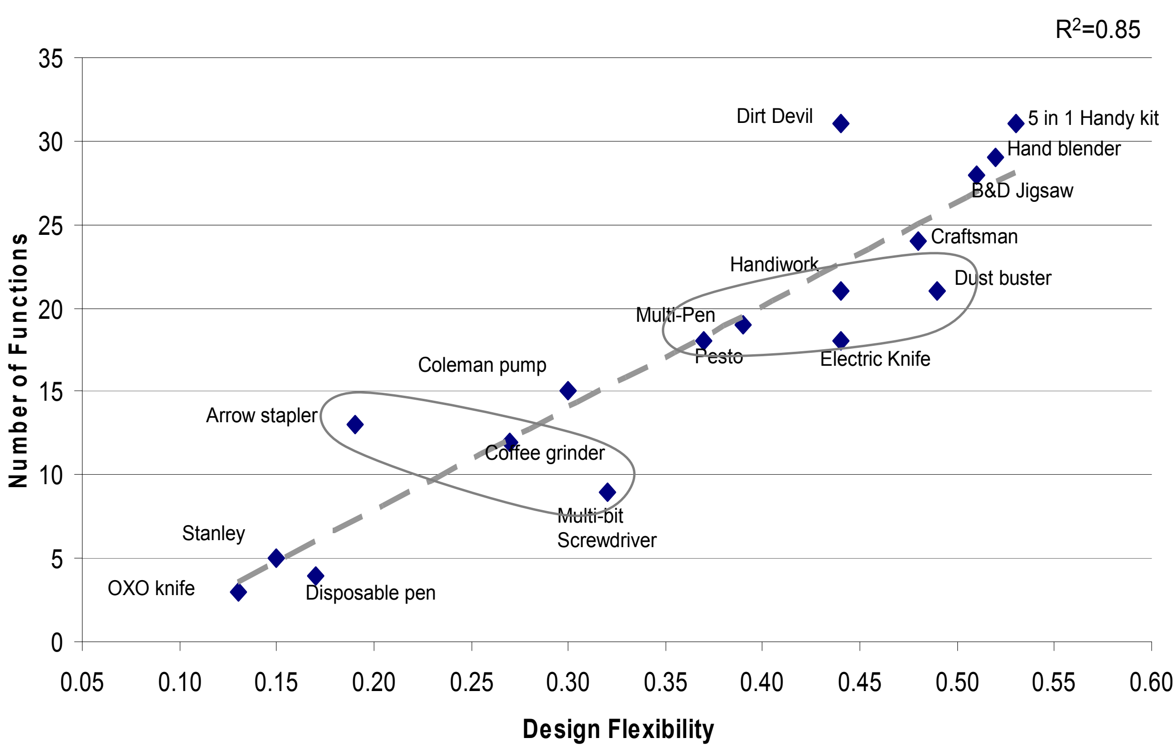

Figure 5. Design Flexibility vs. Number of functions

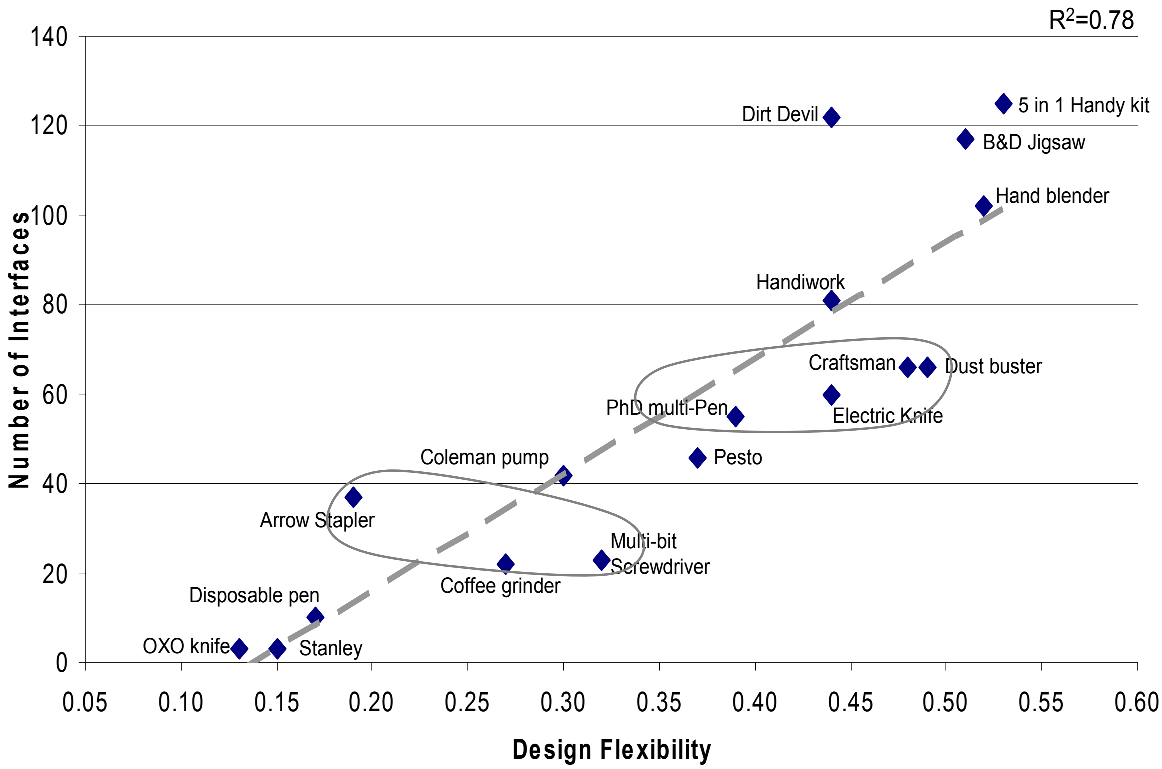

Figure 6. Design Flexibility vs. Number of interfaces

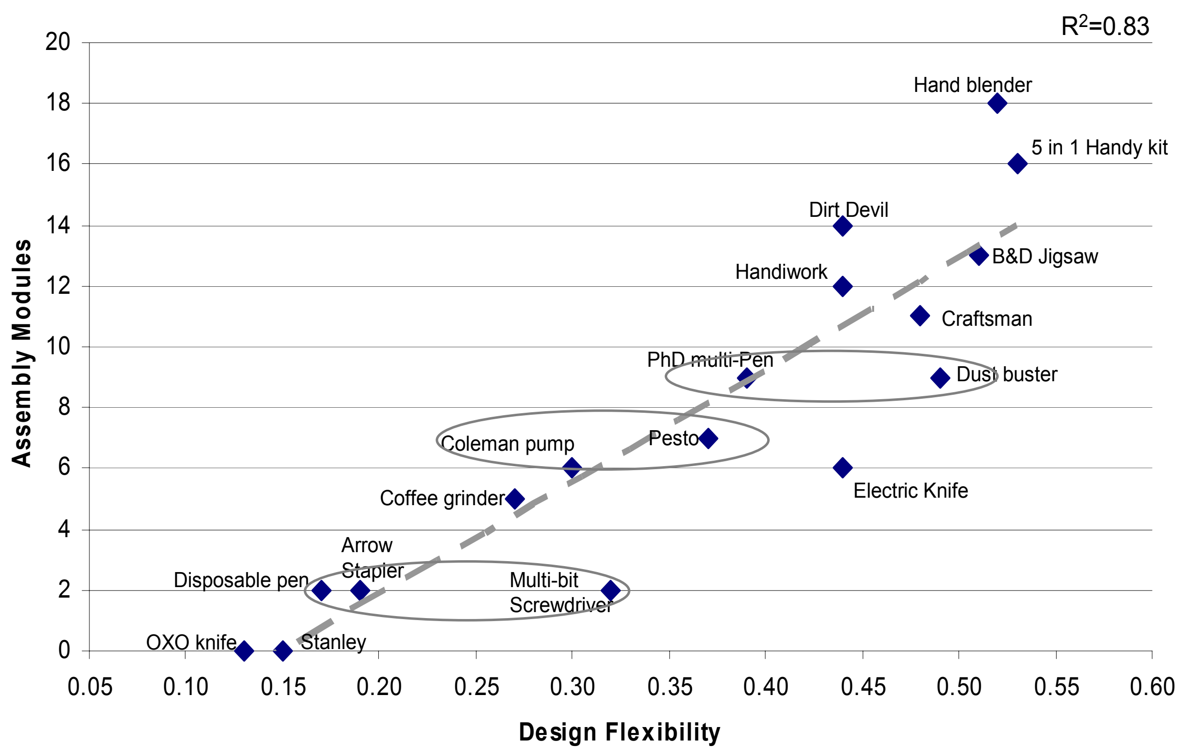

Figure 7. Design flexibility vs. Number of assembly modules

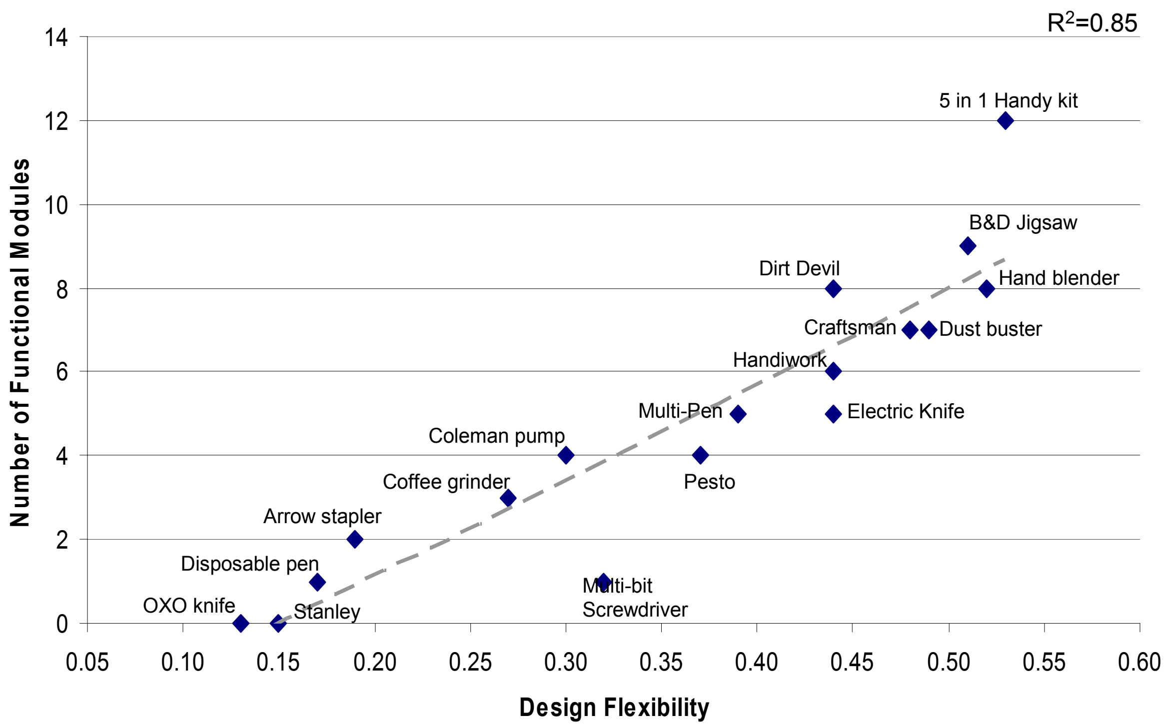

Figure 8. Design Flexibility vs. Number of functional modules

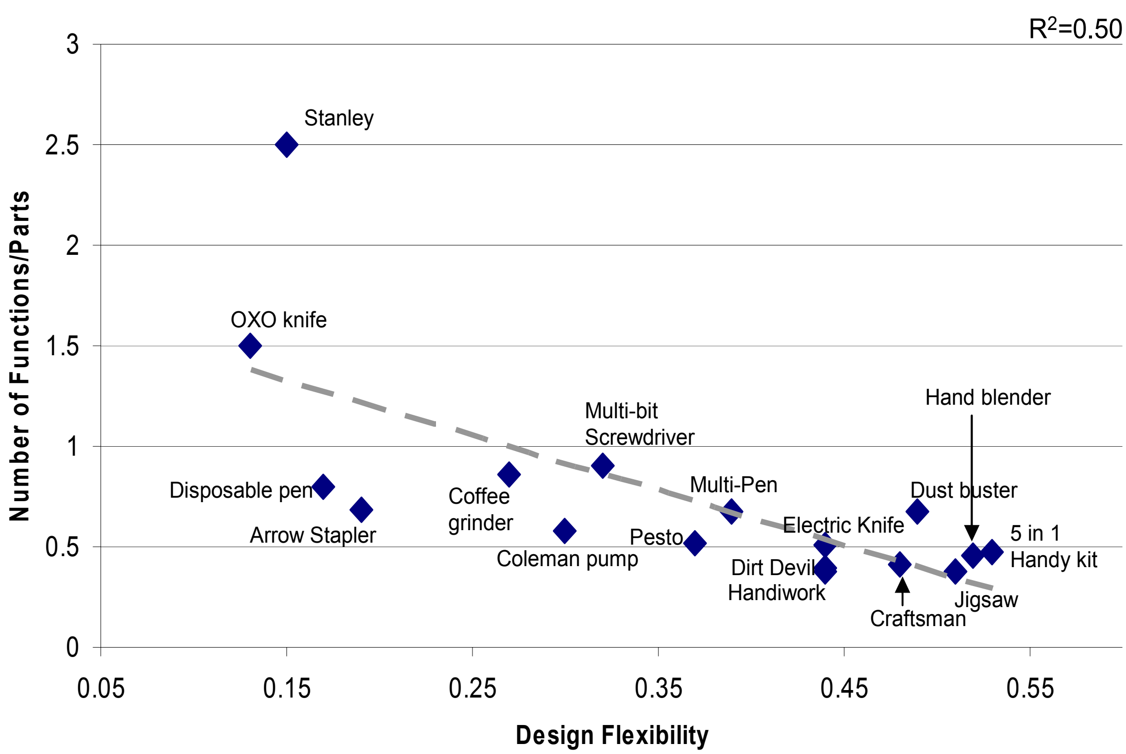

Figure 9. Design Flexibility vs. Total number of functions/parts

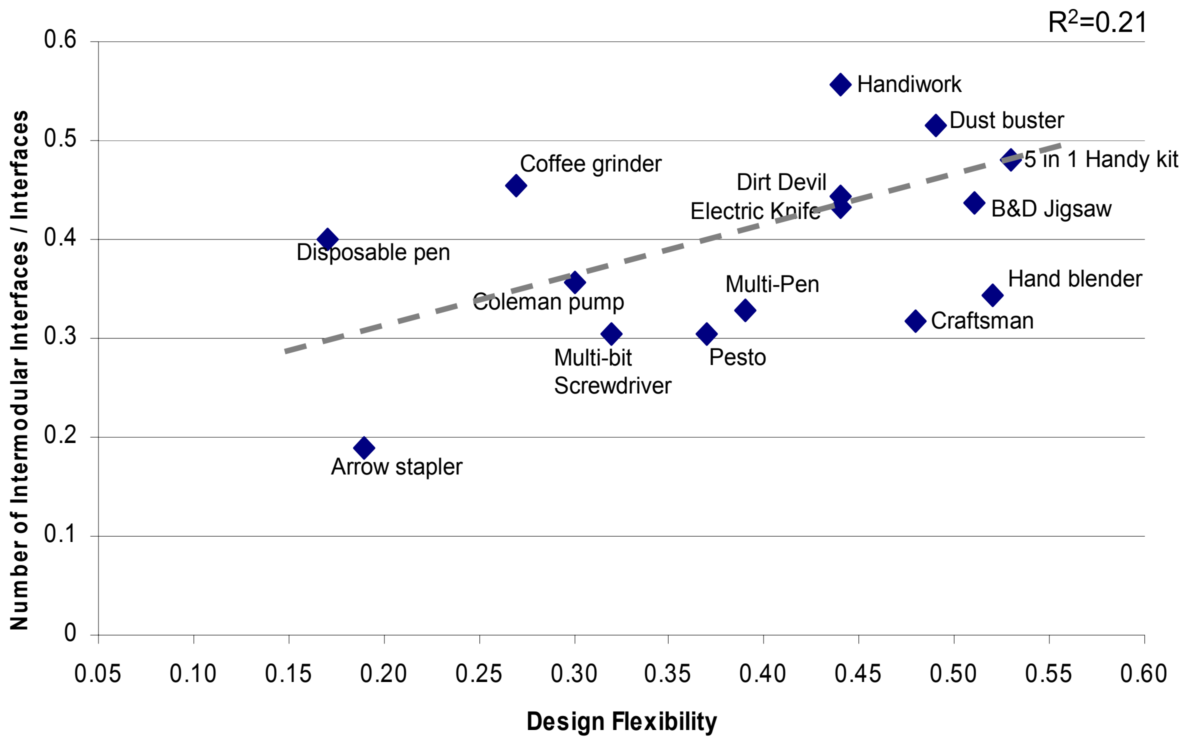

Figure 10. Design Flexibility vs. Number of Inter-modular interfaces / Total interfaces

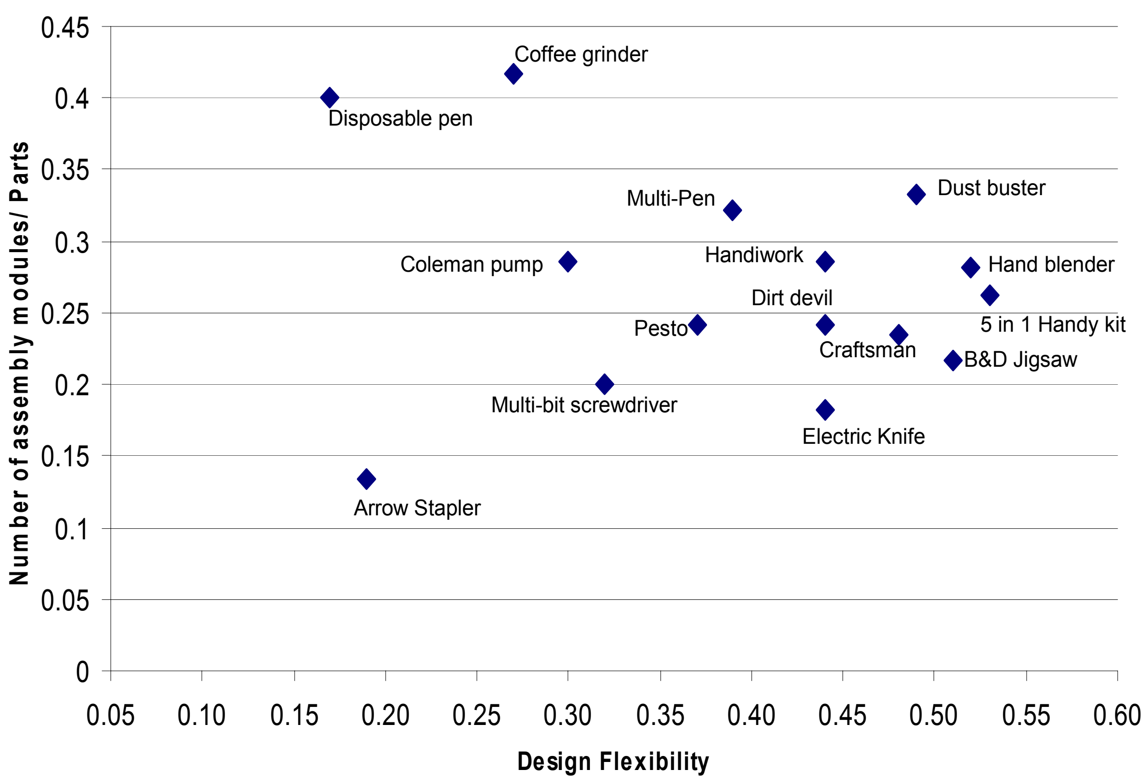

Figure 11. Design Flexibility vs. Number of assembly modules/ Parts

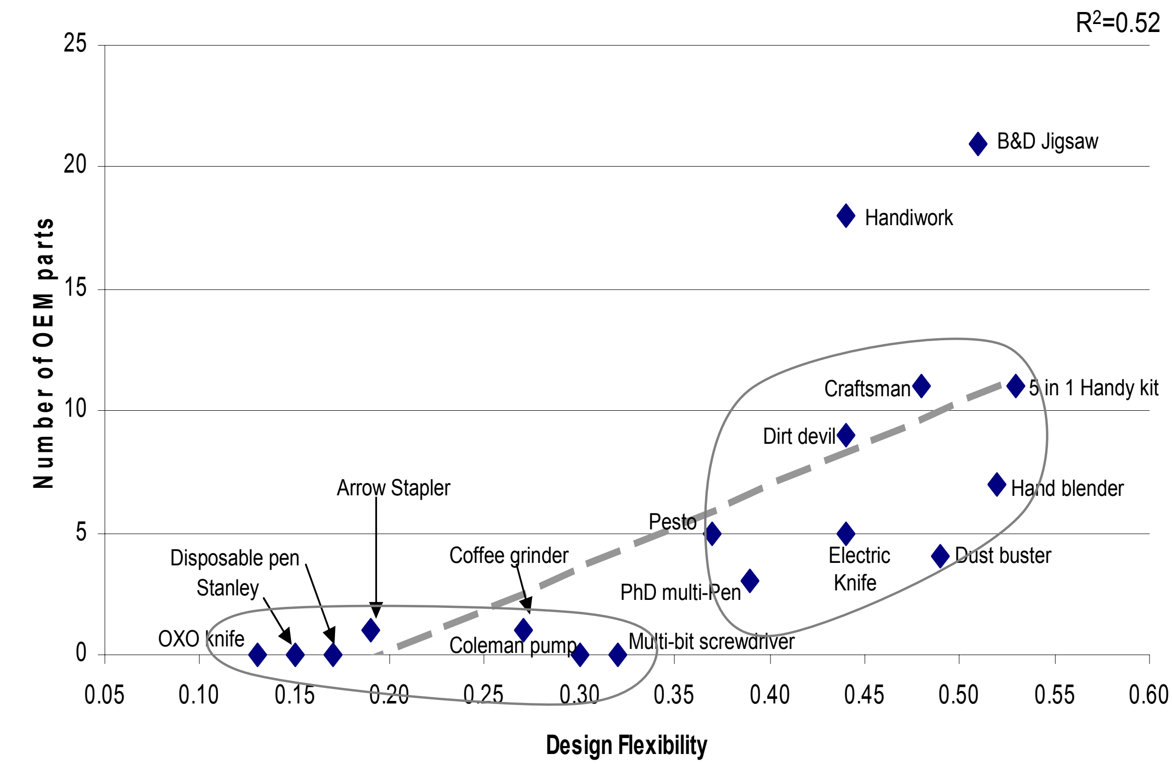

Figure 12. Design Flexible vs. Total number of OEM parts

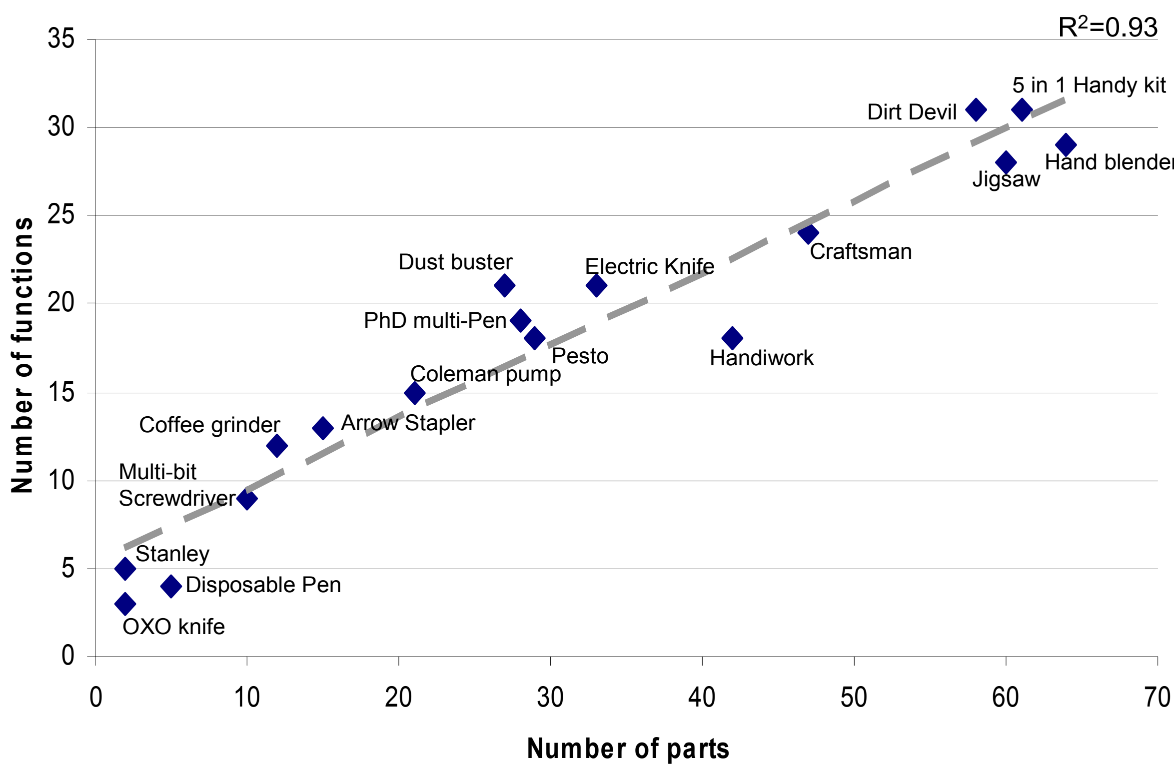

Figure 13. Number of parts vs. Number of functions

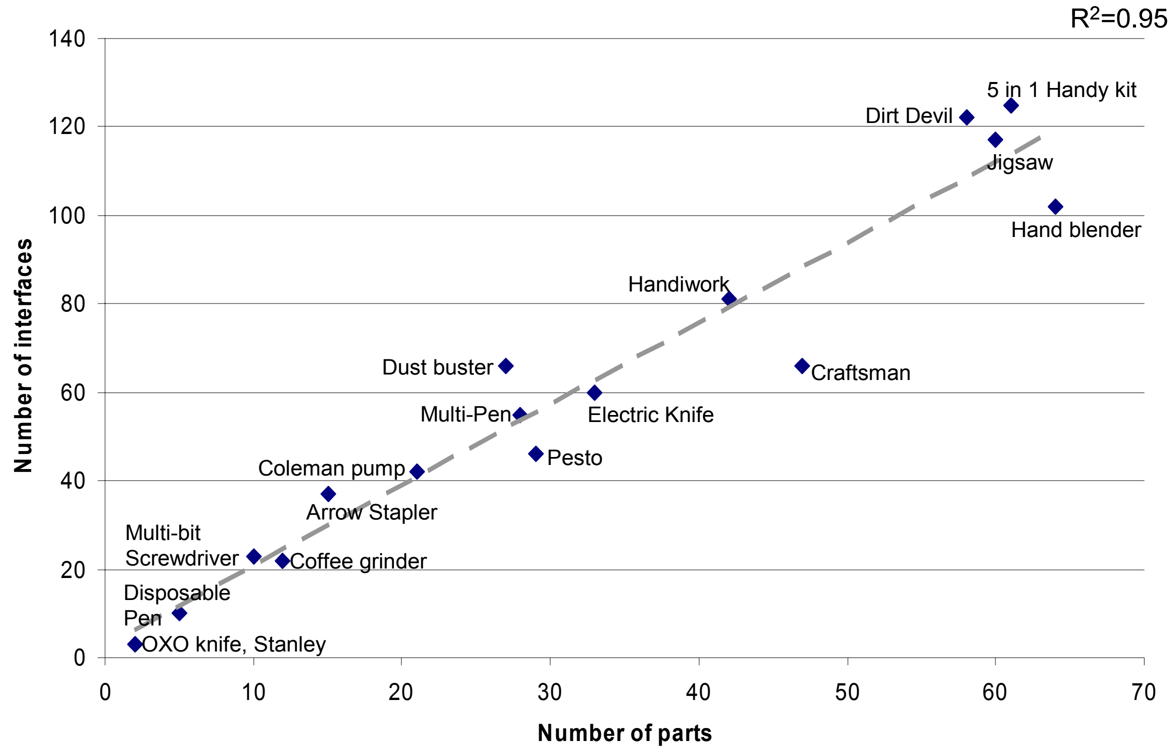

Figure 14. Number of parts vs. Number of interfaces

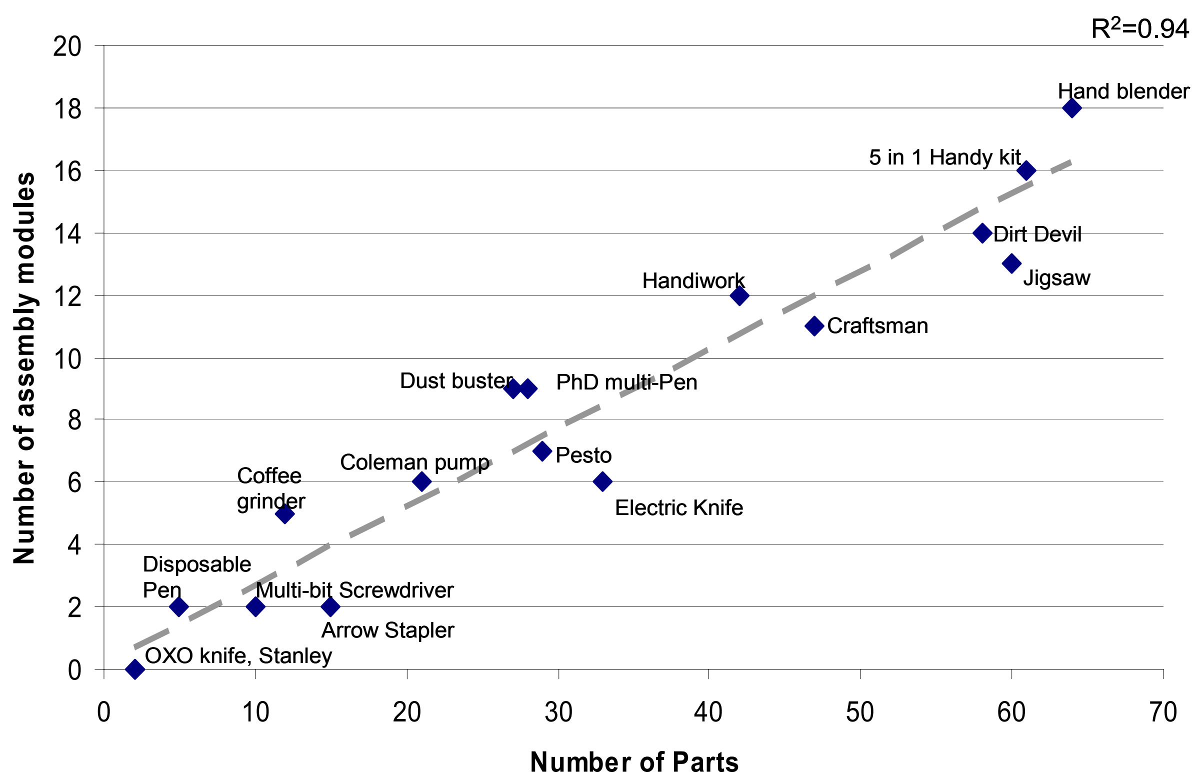

Figure 15. Number of assembly modules vs. number of parts

Now coming again to Figures 4,5 and 6 we observe roughly horizontal regions where significant differences exist in the design flexibility 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 11 with respect to these horizontal regions we found that these products also have same number of modules. For example in Figures 4, 5 and 6 consider the horizontal region which consists of the Dust buster, Electric knife, Multi-pen and Pesto salad shooter. In this case we can see that the Dust buster 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 11 we can see that the Dust buster 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 10, which is a plot between the ratio of number of inter-modular interfaces and interfaces with design flexibility. 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 Figure 7. However based on the DSM observations and the 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 & Multi-pen) are enclosed inside the housing. This can observe in Figure 16& 17 where the Dust buster is more flexible and has more number of external modular attachments when compared to Multi-pen.

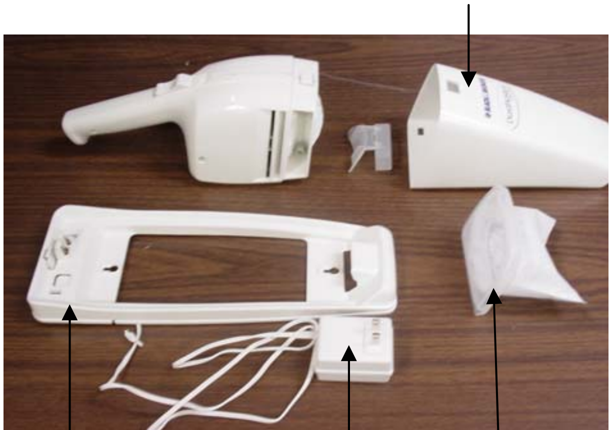

Figure 16. Dustbuster Cordless Vacuum (B&D) DB250C

Figure 16. Paper-mate Multi-pen

Figure 11, is a plot between ratio of number of assembly modules and parts with flexibility. One can observe that the data is a sparse pattern with no clear overall trend. This shows that flexibility is independent of the number of parts in a module. This is an important finding because this suggests the designer that increasing of decreasing the number of parts in a module does not affect flexibility. 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.

Figure 12, shows a weak overall trend that suggests the number of OEM parts is directly proportional to the flexibility. In this figure one can notice two groups of data, which are highlighted. The group that has less flexibility 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 dint 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.

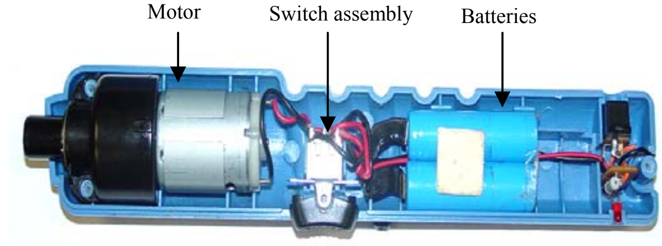

Figure 17. Handiwork Screwdriver with housing removed.

Figure 13,14 and 15 show the correlation between the physical parameters like number of parts, functions, modules, interfaces. We can observe a strong correlation between them. The effect of interdependence of these physical parameters on the design flexibility will be analyzed in our future work.

6.0 CONCLUSIONS AND FUTURE WORK

The overall objective of this paper is to understand the various physical parameters that correlate with product flexibility. We show through an empirical evaluation of seventeen products that product flexibility is affected by physical parameters 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.*
2) *Designing the modules in a product as external attachments makes the design even more flexible.*
3) *As the design becomes more integrated it becomes more inflexible for redesign.*
4) *Designing with more standard components and interfaces will improve product flexibility.*
5) *Directed partitioning of a design into a greater number of elements (manifested through higher numbers of components and functions) improves the flexibility.*
6) *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 his 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 parameters be used to derived a generic flexibility metric?

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