An empirical foundation for product flexibility

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Product flexibility has gained recent attention in companies, which design products for rapidly changing technologies and which are under constant pressure to frequently upgrade their products. In this paper, we develop a method to evaluate product flexibility by performing an empirical study that examines the dependency of flexibility on the number of parts, functions, interfaces, types of interfaces, modules, and the manner of module arrangement. Additionally, a set of guidelines is derived from this study to aid in designing for flexibility.

Keywords: product development, design methodology, design tools, design research, evaluation

Products evolve as a result of various factors such as changing customer needs, improved manufacturing methods, new technologies, legal and regulatory policy changes. Product evolution often follows an S-curve (Otto and Wood, 2001), where evolutions may occur slowly, rapidly, or discontinuously by leaps in technical innovation and performance. Evolution and change are inherent in the nature of product design and so, we should design products to account for this inevitable effect.

Manufacturers strive to be on the forefront of the latest product evolution. In a business context, it is highly desirable to have the capability of evolving a product at minimum cost and minimum time. For years, much research was focused on flexible manufacturing systems, as the ability to easily retool is clearly advantageous. In this

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research, we draw attention to the design of a product itself, as an entity which should be flexible to change.

A premise of this work is that product evolution involves changing a design to a future, as yet unknown solution. This unknown factor creates a difficulty, since the problem is to engineer a solution that can easily accommodate future redesigns. How does one know if a design is easy to redesign? How does one make a design flexible? The central purpose of this work is to understand the issue of flexibility and to develop a method for evaluating product flexibility. Such an evaluation tool can be used by designers for benchmarking, concept evaluation, and ultimately for improving the flexibility of a design. Benefits of a flexible design offer manufacturers the option to reduce time to market and effectively shortcut the evolution cycle.

1 Literature survey on product flexibility

In this section, previous work on product flexibility and the efforts to define and measure product flexibility is compiled. The few metrics that have been developed in the past are derived from research work on flexible manufacturing systems. Based on interviews with managers in manufacturing firms Gerwin (1982) defines two types of flexibilities related to product flexibility: part flexibility (the addition or removal of new components to a system) and design-change flexibility (design changes to a particular component in a system). Furthermore, Gerwin defines two types of flexibility, which are related to products based on the uncertainty faced by manufacturing managers:

a) Changeover flexibility: This is the ability of a process to deal with additions to and subtractions from the mix over time. Uncertainties in the length of product lifecycles lead to changeover flexibility.
b) Modification flexibility: This is the ability of a process to make functional changes in the product. These minor changes are due to the uncertainties in the customer needs, which arise at the beginning of the lifecycle for a standardized product or throughout the lifecycle for a product that can be customized.

When studying the changing nature of flexibility in the body framing process of two American automobile assembly plants, where flexible automation had replaced manual equipment, Gerwin (1987) uses a qualitative scale to measure component (changeover) flexibility and modification flexibility. In this study, Gerwin rates these systems based on the ability and time to accommodate major or minor design changes in the product. He concludes that the modification flexibility is increased due to the ability to re-program the robots.

When classifying the different types of flexibility in manufacturing systems, Browne *et al.* (1984), explains product flexibility as the ability to change in producing a new product or set of products very economically and quickly. They measure product flexibility, as the time required to switch from one part mix to another, not necessarily of the same part types. Moreover, they explain that this flexibility can be achieved by having: an efficient and automated production planning and control system; and machine flexibility, where machine flexibility is the ease of making the changes (on the machine) required to produce a given set of parts types.

While comparing the flexible manufacturing systems (FMS) in the United States and Japan, Jaikumar (1986) uses the number of parts introduced per year, as a measure of product flexibility. In their work on advanced manufacturing systems, Son and Park (1987), describes productivity, quality and flexibility as the critical measures of manufacturing performance to justify the investment in integrated manufacturing and production systems. In this study, they define four different types of flexibility measures based on equipment, product, process and demand. Product flexibility, for this study, is defined as the adaptability of a manufacturing system to changes in product mix. Because of changing market demand, the lifecycle of the individual products is shortened. This reduction in turn leads to a smaller lot size, but more variety. Based on this result, they view the key to improving product flexibility is to reduce the setup cost in spite of the small lot size. Accordingly, the product flexibility for a given period is defined as:

$$\mathrm{FP} = \frac{O_{\mathrm{T}}}{A} \tag{1}$$

where A is the setup cost and O_{T} is the output produced by the manufacturing system (usually expressed in units of physical volume, such as pieces, tons, etc.).

Based on an extensive survey done on flexibility in manufacturing, Sethi and Sethi (1990) define product flexibility as 'the ease with which new parts can be added or substituted for existing parts. In other words, product flexibility is the ease with which the part mix, currently being produced, can be changed inexpensively and rapidly.' Moreover they state that the new parts in this definition cannot be arbitrary, which means that the changes occurring in the current design are not unknown.

2 Foundations of flexibility

The flexibility issue is rooted in the evolutionary process of product design and redesign; key to this process is the event of change. Each evolution involves some change which can probably be classified in many ways, such as adaptive redesign or parametric redesign (Otto and Wood, 2001). One problem is to characterize a change in a meaningful way that facilitates analysis. Here, we simply refer to this change as a change mode, which is comparable to the failure mode in failure modes and effects analysis (Benjamin and Wolter, 1998) (FMEA). The relation between the concept of change and product evolution leads to a definition of flexibility. Changes that occur, during an evolution, dictate the cost of that evolution. The higher the cost, the less flexible the product is for a given evolution and the related set of changes. Flexibility is then defined as the ease with which a set of changes can be imposed on a given design solution.

While the engineering and manufacturing capacity influence flexibility, we focus on the product itself as a reflection of flexibility. For example, some products are clearly more flexible than others to redesign. Table 1 gives five pairs of examples of products, which are relatively more flexible, when compared to counterparts. For example in Figure 1, a lego machine (Figure 1b) is relatively more flexible, when compared to a machine using custom-designed widgets (Figure 1a). Even with only five pairs of examples, several details of flexibility emerge. First, it is clear that flexibility is highly dependent on the particular change in question. As a result, it is very difficult to discuss comparisons between vastly different products. The screwdriver case illustrates the general notion of change propagation. In the removable bit style, a change to that region of the device does not propagate beyond the interface of the bit module. Part of the anecdotal relation between flexibility and modularity seems to be the inherent partitioning effect that modularity causes. The structural frame example between a monolithic unit and a comparable unit that exhibits a greater degree of partitioning illustrates this point.

Table 1 Examples of flexible and inflexible products

Inflexible	Flexible
Old style screwdriver	New style with removable bits
Machine using custom-designed widgets	Lego machine
Wooden chair	Modern adjustable chair
Manual engine lathe	CNC lathe
Monolithic structural frame	Structural frame partitioned into sections

(a)

(b)

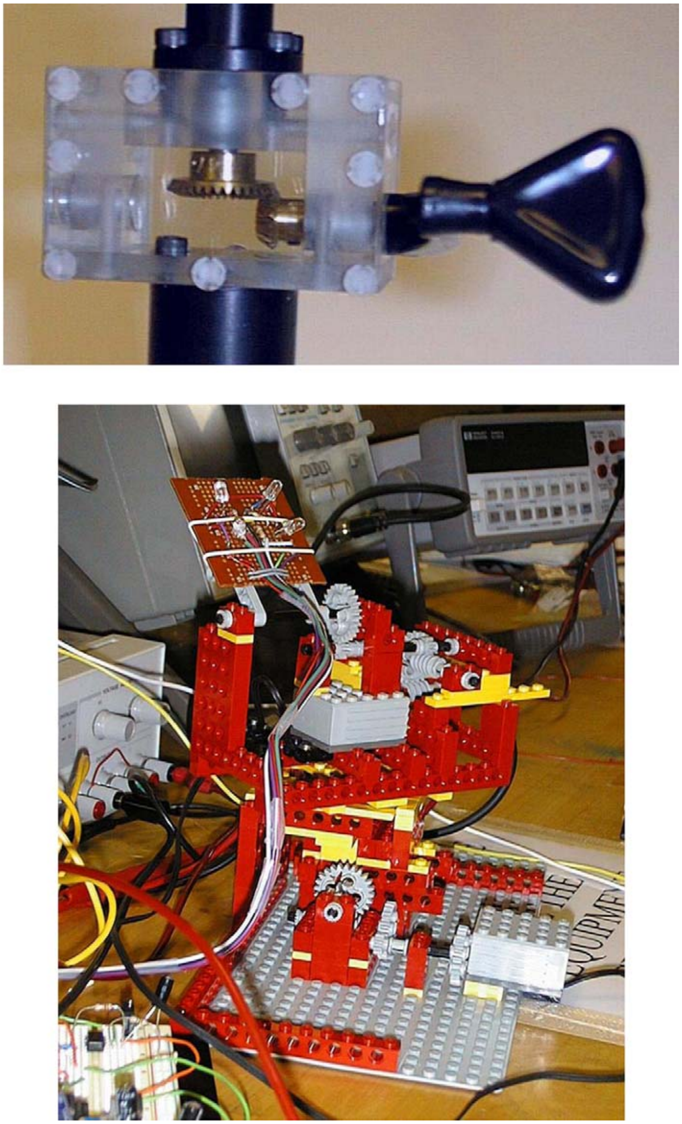

Figure 1 (a) Machine using custom-designed widgets (a custom machined gearbox). (b) Lego machine (a light tracking mechanism using lego gears and a lego structure)

That is, some relation exists between the partitioning, granularity, or resolution of a device and the flexibility in changing the design. A decomposed artifact offers the potential for localizing change.

Standardization of components and interfaces affects flexibility, as illustrated by a hypothetical comparison of a lego device and a custom machine, designed and fabricated from raw materials. The preference of OEM machine elements, such as motors, hydraulic cylinders, pumps, bearings, couplings, gears, valves, fasteners, etc., over custom units is common practice in machine design. One effect, in taking a standardized approach, is the impact on product flexibility.

The issue of flexibility is closely related to the notion of reconfiguration, where fast and low cost reconfiguration is analogous to a high flexibility. In this sense, a mechatronic system, controlled through software, is highly reconfigurable, whereas a product with hard-wired behavior is less flexible. A CNC lathe compared to a manual engine lathe illustrates this case; however, this paper is concerned with design flexibility – not end-use (or user) flexibility. All other functionality and performance values being equal, a CNC machine has a greater flexibility for user reconfiguration than a manual machine. In particular, a CNC machine can readily be reconfigured (programmed) to machine a part of highly complex geometry, while a manual machine would require the operator to increase his skill level so high that for practical purposes, a human operator could never machine such a complex part.

Continuing with the CNC machine example, both machines differ greatly in user flexibility, but are not necessarily different in terms of design flexibility, assuming the only distinction is software control vs. manual control. This research seeks an understanding of design flexibility regardless of user operation. In another example, a modern office chair is highly adjustable by the user compared with a conventional wooden chair. Despite the obvious differences in user flexibility, the design flexibility is a related, but separate issue. How does one design a chair, in either a fixed or adjustable configuration, to be easily redesigned?

The above examples illustrate some characteristics of flexibility and offer a hint of possible relations among flexibility and various design factors, such as standardization, modularity, and the propagation of change within a device. In order to systematically account for the variables influencing design flexibility, we explore and develop an evaluation tool based on an empirical study of products. In the end, this approach leads to a better understanding of flexibility, an evaluation method, and a set of guidelines for designing for flexibility.

3 Methodology: assessing product flexibility

3.1 Change modes and effects analysis (CMEA) (Palani Rajan, 2003; Palani Rajan et al., 2003)

Based on the complexity of the problem of assessing product flexibility, and from our initial observations on consumer products from the market, we first select an established method used in industry to solve analogous problems. A widely used method, failure modes and effects analysis (Benjamin and Wolter, 1998) (FMEA), provides a good first analogy to the evaluation of 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, referred to as change modes and effects analysis (CMEA), is explained as a two step procedure as follows:

3.1.1 *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 in terms of modules and parts. Decomposing the products based on the functions (Stone and Wood, 1999, 2000) offer more assistance in the conceptual design stage, when we are not sure about the final form of the product.

3.1.2 *Step 2: forming the CMEA table*

The second step in this method is to assess the 'Change Potential Number' (CPN) of a product for possible changes. The 'Change Potential Number' gives an indication of how easily a change can be incorporated into 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 in the evaluation of CPN. In this section, we propose a systematic process for this analysis. The CMEA table shown in Table 2 is used to find CPN. The basic columns in the CMEA table shown in Table 2 are design flexibility, occurrence and readiness. These are the three main metrics used to determine the CPN of the products. The other columns are supportive

Table 2 Generic change modes and effects analysis basic columns

Change Modes and Effects Analysis for Potential Changes in Product Design													
									Action Results				
Modules / Parts	Potential change modes	Potential effects of change	Design flexibility	Potential cause(s) of change	Occurrence	Readiness	Change of potential number	Recommended actions / Guidelines	Actions taken	Design flexibility	Occurrence	Readiness	Change of potential number

columns to help the designer to access these three main metrics. The basic columns in this table are explained as follows:

3.1.2.1 *Modules/Parts*

This column can be components or sub-assemblies or even functions, depending on the complexity of the product under study. Each of the constitutive parts of a product will be examined independently and their result will be added together to create the CPN.

3.1.2.2 *Potential causes of change*

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

3.1.2.3 *Potential changes*

In this column of the 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 function. For example consider a module, such as a DC motor. A possible change might be to increase or decrease motor power.

3.1.2.4 *Potential effects of change*

The various effects of a particular change on other parts or functions of the device are documented in this column, after a brief brainstorming session by the designer. These effects can be interpreted as the ripple that this change causes to 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 altered due to the geometric dependency between the motor and the housing.

3.1.2.5 *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 of 1–10, as shown in Table 3. Here ‘1’ means minimum flexibility and ‘10’

Table 3 Generic change modes and effects analysis design flexibility table

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

means completely flexible. The product with high flexibility ranking means that for any future change the redesign cost is low. The scale in Table 3 was followed throughout our empirical study described in later sections.

3.1.2.6 *Occurrence*

This occurrence 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 of 1–10, where ‘1’ means no or very few occurrences and ‘10’ means that the change is inevitable. This measure is based on exogenous parameters, such as changing technologies or market niche and not physical attributes of the product. Therefore, a product with a low occurrence ranking means the probability of any future change occurring in that design is minimal, which in turn leads to a lower redesign cost. It follows that a product with a low occurrence ranking is more flexible. This probability of occurrence may be determined based on the rate of occurrence of these particular changes, where these changes can be broadly categorized as follows:

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

Table 4 Generic change modes and effects analysis occurrence table

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

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

Shown in Table 4 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 4 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.

3.1.2.7 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 of 1–10, where '1' means the company is completely prepared to go ahead with this change and '10' means that the company is completely unprepared. This implies that the product with high readiness ranking means that 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 counterpart with low readiness. The factors to be considered, during ranking readiness are elaborated in Table 6. An example of a generic CMEA readiness table is shown in Tables 5 and 6.

3.1.2.8 Change Potential Number (CPN)

The CPN is defined as follows:

$$\mathrm{CPN} = \frac{1}{N}\sum_{i=1}^{N}\frac{[(Ri+Fi)-Oi+8]}{27} \qquad (2)$$

where F is design flexibility, O is occurrence, and R is readiness. N corresponds to the maximum of the number of potential change modes, the number of potential effects of change, or the number of potential causes of change.

Table 5 Generic change modes and effects readiness table

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

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 formula, a completely flexible product is one in which the redesign cost incurred is 0$ for any future change in the design. The accuracy of these metrics is evaluated by conducting simple sensitivity analysis of these three main factors, namely design flexibility, occurrence and readiness. The errors in accessing the three main metrics are assumed to be ± 1, on an interval scale of 1−10. Using this premise, the overall flexibility sensitivity is ± 0.11.

3.1.2.9 *CPN derivation*

The formula from Eq. (2) has been created, such that the CPN is linearly related to the three factors and normalized between zero and one. As discussed above, the higher the value of CPN the more flexible the design. Now consider these three terms, *F* (design flexibility), *O*

Table 6 Factors to be considered to assess readiness (*R*)

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 latter. 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 to 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

Table 7 Conditions for an ideally flexible product for a particular change

Terms	Description	Value	Sign
R	The organization should be completely ready for this change	10	+
F	This change should cause a minimum effect or redesign to other parts or modules in the design	10	+
O	This change should have a low probability of occurrence	1	–

(occurrence), and *R* (readiness) in Eq. (2). If a product is ideally flexible for a change, the signs and the values of these terms should be assigned as explained in Table 7. Given an extreme example, this table indicates that if a product can accommodate a change with no redesign cost, and if the probability of occurrence of this change is low, this product is completely flexible for this change. The number '8' in the numerator and '27' in the denominator of Eq. (2) is added to bound the CPN from 0 to 1.

3.2 Change modes and effects analysis – flow chart

In the previous section the different columns in the change modes and effects analysis (CMEA) were addressed. Figure 2 explains the CMEA method as a sequential flowchart. To assess the overall flexibility (CPN) of any product design, as explained in this flowchart, the designers systematically follow the flowchart steps. This flowchart explains the method in terms of inputs needed and the outputs obtained, during execution of this method. When applying this method to a product, the major inputs needed are a list of all possible causes of changes that can occur in the product under investigation and a table for assessing design flexibility (*F*), occurrence (*O*) and readiness (*R*). The major outputs to the designers, during the study, are an in-depth analysis on particular changes and its effects on the entire product and a measure of flexibility of the product overall.

3.3 Illustrative example

In this section, we describe the CMEA method, as applied to a Braun Coffee Grinder shown in Figure 3. The sequence of operations to be followed for this CMEA method is explained in Figure 2. A partial CMEA analysis on this product is shown in Table 8.

3.3.1 Step 1: decomposing the product

The product under study is disassembled, and a list of components and modules are noted in the 'Modules/Parts' column of CMEA table (Table 8).

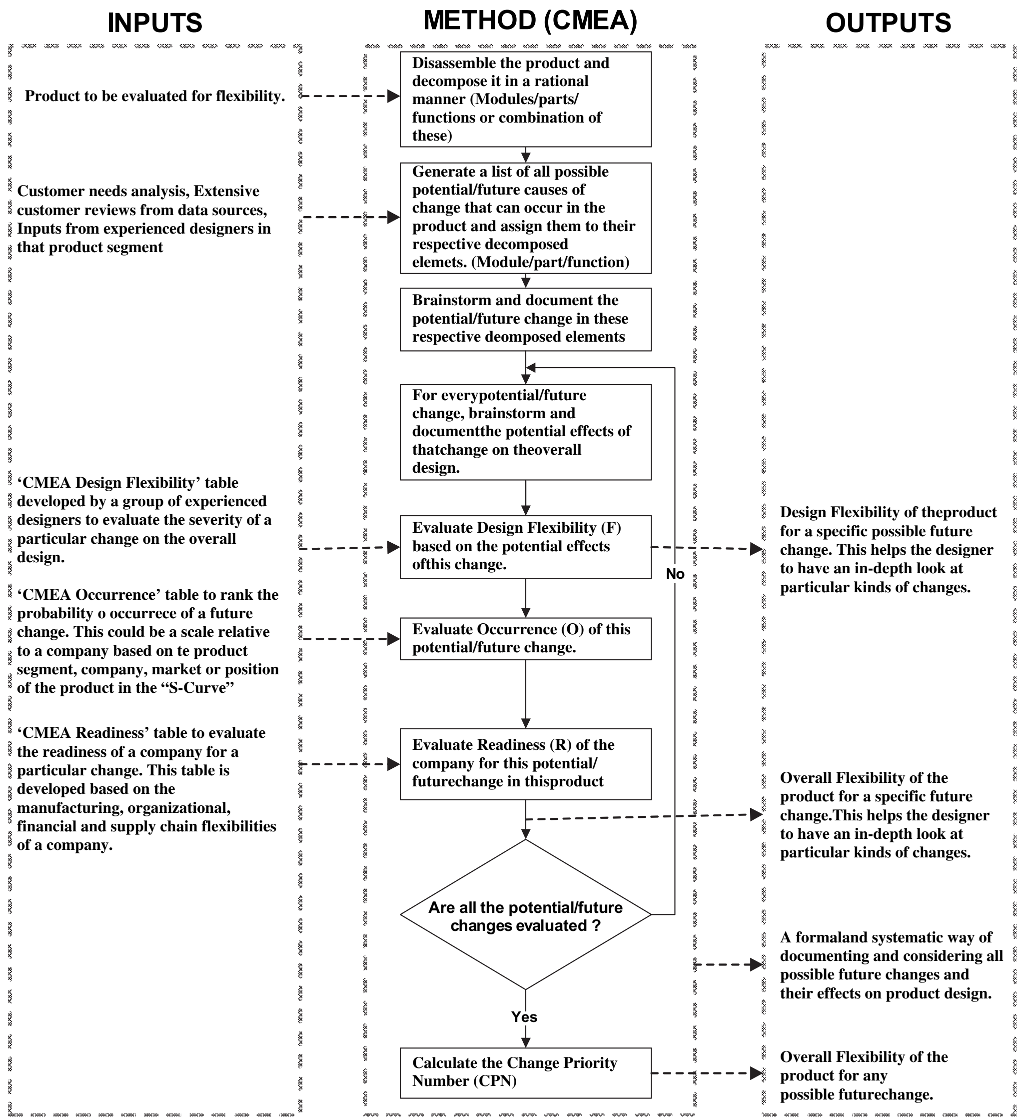

Figure 2 Change modes and effects analysis method sequence of operations flow chart

3.3.2 Step 2: forming the CMEA table

The first step in this process is to gather the customer needs by studying extensive reviews from data sources, such as various websites like http://www.amazon.com, http://www.epinions.com, warranty information, etc. These reviews are searched to find indications of deficiencies in the current design, which are presumed to be reasonable approximations of

Figure 3 (a) Braun Coffee Grinder (b) Grinding Cup Assembly

the type of stimuli that spurs 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

Table 8 Partial change modes and effects analysis for Braun Coffee Grinder

Modules/Parts	Potential Change Mode	Potential Effects of Change	Design Flexibility	Potential Cause(s) of Change	Occurrence	Readiness	Change Potential Number
Grinding cup assembly	Make this module detachable, so that it can be cleaned easily	This might lead to minor modifications in the housing die, and some redesign in the grinder module	2	Impossible to thoroughly clean hopper! Need more holding capacity for beans	7	7	0.63
Electric cord assembly	OEM change	This is a OEM module	8	Need a long cord	5	10	0.59
Motor assembly	Changing the performance characteristics of the motor or reducing the size of the motor	This modules is not an OEM the motor is assumed to be manufactured in-house, change in the motor might affect the housing die	2	Noisy, hops beans in stead of milling them. Over-powered motor!	4	7	0.74
No of potential effects of change	10						0.63

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 3, the design flexibility (F) ranking for the particular change in the design is assigned. In the Braun Coffee Grinder example in Table 8, consider the 'Grinding Cup Assembly' (Figure 3b) where the 'Potential change mode' is '*Make this module detachable and modular, so that it can be cleaned easily*.' and 'Potential effect of change' is '*This will lead to modifications in the housing die and redesign of the grinding cup assembly*.' The housing is an expensive module due to the cost in creating a new die. Moreover except for the motor assembly, almost all other modules might have to undergo a redesign, because of this change. Hence, it is indicated as a 'Total redesign with some reuse of parts', according to Table 3.

Assessing the occurrence (O) of a particular change, requires more rigorous customer reviews and opinions of experienced designers in this particular consumer product segment. In order to assess the occurrence (O) of these 'Potential cause(s) of change' for this study, the collected customer needs and reviews are ranked, based on their importance and number of times they occurred, during the data collection process. This rating is 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 do not have a rigorous basis for assigning the readiness (R) for a particular change, in order to demonstrate this method, we use an assumption for providing the ranking in Table 8. This ranking is based on company size. In Table 8, the readiness (R) ranking for a change in the 'Grinding Cup Assembly' of the Braun Coffee Grinder is assessed as '7', since Braun is a well established company compared to a company just entering the market on a small manufacturing scale. Braun is then considered to be more ready to make this change, when compared to competing manufacturers. Finally, the CPN for this product is calculated using the formula in Eq. (1), where N is the number of potential change modes in this example.

3.4 Validation of CMEA

In order to validate the proposed technique, we conduct a pair-wise empirical study on a set of products available in the market. The products considered for this experiment range from small-to-medium scale consumer products. A set of 10 are chosen and differentiated, as flexible and inflexible, by experienced designers. Each of these products is assessed for flexibility by systematically applying the CMEA method, as explained in Figure 2. The customer needs, required to generate the 'Potential causes of change', were gathered by studying extensive reviews from data sources, like http://www.amazon.com and http://www.epinions.com. In order to address all three of these factors of design flexibility (F), occurrence (O) and readiness (R), a significant level of industrial interaction is required. Given practical constraints, we choose to evaluate the products with design flexibility (F) alone. Table 3 is used to assess the design flexibility (F) of the product design for various possible future changes. Eq. (2) is then reduced to:

$$\text{Design flexibility} = \frac{1}{10 \times N} \sum_{i=1}^{N} Fi \tag{3}$$

Table 9 shows the set of 10 products, which are evaluated using CMEA on a pair-wise basis. The design flexibility (F) ranking for this set of products is also shown in Table 9. For each pair of products, the first product was considered more flexible, when compared to the second product according to the experienced designers. Overall, a t-test confirms that the flexibility rankings are distinct between the flexible and inflexible set with over 99% probability. In the very first pair, the

Table 9 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	B&D Dustbuster	0.49
2	Arrow Light Duty Stapler	0.19
1	Handiwork Screw Driver	0.44
2	Stanley Screw Driver	0.17
1	B&D Electrical Knife	0.44
2	Oxo Good Grips Knives	0.13
1	Sanford Multi-purpose Pen	0.39
2	Disposable Pen	0.17

Black and Decker Jig Saw is considered to be more flexible, when compared to the Braun Coffee Grinder. It appears the CMEA is able to capture this qualitative difference in flexibility, where the Black and Decker Jig Saw is given a design flexibility (*F*) number of '0.51', while the Braun Coffee Grinder is '0.27'. While this example is limited, it suggests that the CMEA captures the difference in the design flexibility (*F*) of these products, when comparing them on pair-wise basis.

4 Principles of flexibility based on empirical study

In this section, we examine product flexibility by conducting an empirical study on existing products in the market. Physical factors, including number of parts, functions, interfaces, type of interfaces, modules, the way these modules are arranged, and the presence of OEM parts are analyzed in terms of their relationship to product flexibility. This research involves plotting these factors against the design flexibility measure, *F*, derived previously. From this, a second set of insights is derived in order to codify knowledge of flexibility, as it relates to the above factors. This action is a significant step and advances us to our future objective of developing a generic metric for quantifying design flexibility, based on directly measurable characteristics of an artifact.

The approach includes two major components. The first is an *empirical study* to measure different physical parameters in a product across a sample set of 17 products. These parameters are identified, based on their direct or indirect influence on flexibility. This sample set of 17 products is then evaluated for design flexibility (*F*) by applying change modes and effects analysis (CMEA), as illustrated in Section 3.3. After the products are rated for design flexibility (*F*), they are compared with the physical parameter, measured in the first part of this empirical study by plotting the design flexibility (*F*) of the products in the *y*-axis and the various parameters in the *x*-axis. These graphs are then analyzed in terms of overall trends and phenomena in local regions.

4.1 Empirical study example and method

Consumer products are selected as the data set, because they represent a significant aspect of design focus in industry (Mc Adams *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 and Decker Dustbuster Cordless Vacuum cleaner (Figure 4). We now discuss the complete data collection procedure of this product to show how the investigation of factors, affecting product flexibility, is executed.

Figure 4 Dustbuster Cordless Vacuum (B&D) DB250C

4.1.1 Measuring physical parameters

The following section explains how the measurements are performed. Based on the understanding of the flexibility issue from initial work on CMEA, the following characteristics were chosen: number of parts, number of functions, number of modules, number of interfaces, number of types of inter-modular interfaces, number of intra-modular interfaces, and number of OEM (original equipment manufacturer) parts. These are furthered qualified below.

In order to consistently count the number of functions in a product, the functional models (Otto and Wood 2001) of these products are developed first. Details of the functions, performed by the product, are obtained from the functional models. 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. One important aspect, addressed throughout the study, is the granularity of these functional models. These are maintained on the same level of granularity, as much as possible throughout the study. In order to maintain the granularity of these functional models, customer needs are ranked over a scale of 1–5 (as shown in part in Table 10), 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 important, and '5' means it is a must (critical). The functional model for the B&D Cordless Vacuum is shown in Figure 5. 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.

Table 10 Customer needs analysis of B&D Vacuum

Customer Need	Scaled Customer Need Rating (1–5)
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

An interface (Van Wie *et al*., 2001; Van Wie, 2002) 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'. To document the interface data, we use a component–component style matrix, called 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). The documentation of this physical structure for a Cordless Vacuum is given in Figure 6. The

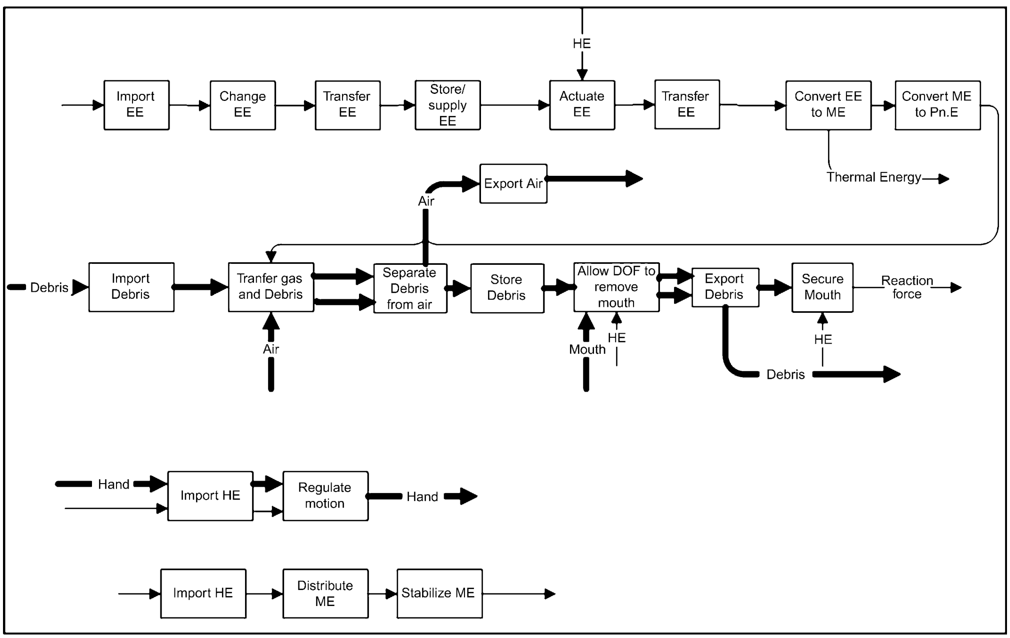

Figure 5 Functional model of B&D Cordless Vacuum

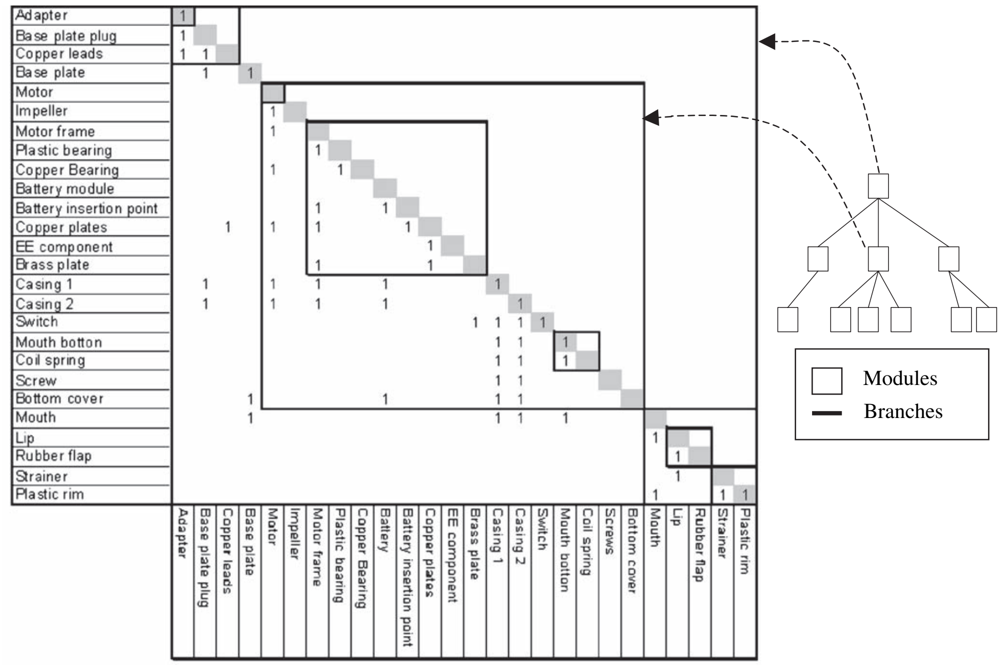

Figure 6 Physical assemblies, components, and interfaces of a B&D Cordless Vacuum

interfaces are identified by marking a ‘1’, whenever two components possess an interface. Similarly, an inter-modular interface is identified as an interface between one or more modules.

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 (Van Wie *et al.*, 2001). A tree structure of the assembly modules and components can be derived from the DSM, so that the hierarchy of parts is clear (Figure 6). This allows one to easily count the number of branches between assemblies and components.

4.2 Results and discussion

The products in this study include 17 consumer devices that are generally small-scale consumer products (e.g. manual screwdriver, hand blender, power tools, etc.). The results are summarized in Table 11 and arranged in a series of graphs that illustrate the relationships among the parameters evaluated in this study. The CMEA analysis is performed on these 17 products and their design flexibility (F) ranking is listed in Table 11. Several interpretations are taken from the graphs, from the

Table 11 Summary of results from the empirical study

Product	Number of Parts	Number of Functions	Number of Assembly 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	125	60	11	0.48	0.47	0.53
Braun Multipurpose Hand Blender	64	29	18	102	35	7	0.34	0.45	0.52
B&D Jig Saw	60	28	13	117	51	21	0.44	0.37	0.51
B&D Dustbuster	27	21	9	66	34	4	0.52	0.68	0.49
Craftsman 3/8 In Drill	47	24	11	66	21	11	0.32	0.41	0.48
Handiwork Screwdriver	42	18	12	81	45	18	0.56	0.38	0.44
Dirt Devil Spot Scrubber	58	31	14	122	54	9	0.44	0.40	0.44
B&D Electrical Knife	33	21	6	60	26	5	0.43	0.51	0.44
Papermate Multi-Pen	28	19	9	55	18	3	0.33	0.68	0.39
Presto Salad Shooter	29	18	7	46	14	5	0.30	0.51	0.37
Multi-Bit Manual Screwdriver	10	9	2	23	7	0	0.30	0.90	0.32
Coleman Quick Pump	21	15	6	42	15	0	0.36	0.58	0.30
Braun Coffee Grinder	12	12	5	22	10	1	0.45	0.86	0.27
Arrow Light Duty Stapler	15	13	2	37	7	1	0.19	0.68	0.19
Disposable Pen	5	4	2	10	4	0	0.40	0.80	0.17
Stanley Screw Driver	2	5	0	3	0	0	0.00	2.50	0.15
OXO Good Grips Knives	2	3	0	3	0	0	0.00	1.50	0.13

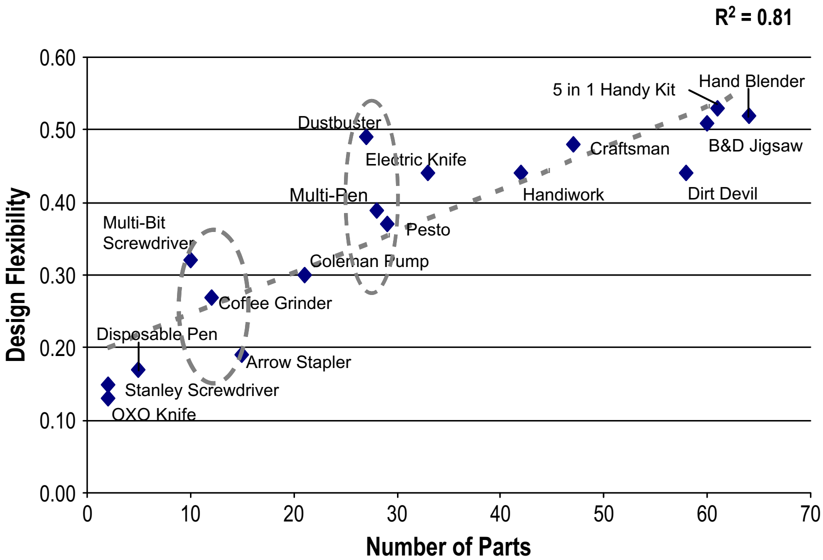

Figure 7 Design flexibility vs. number of parts

perspective of both overall trends and phenomena in local regions. The goodness of fit, that is the R^2 values for these trends are denoted in each of these graphs to show how strongly physical parameters correlate with flexibility.

Figures 7–9 show an overall strong correlation between the number of parts, functions and interfaces with design flexibility (F). From these

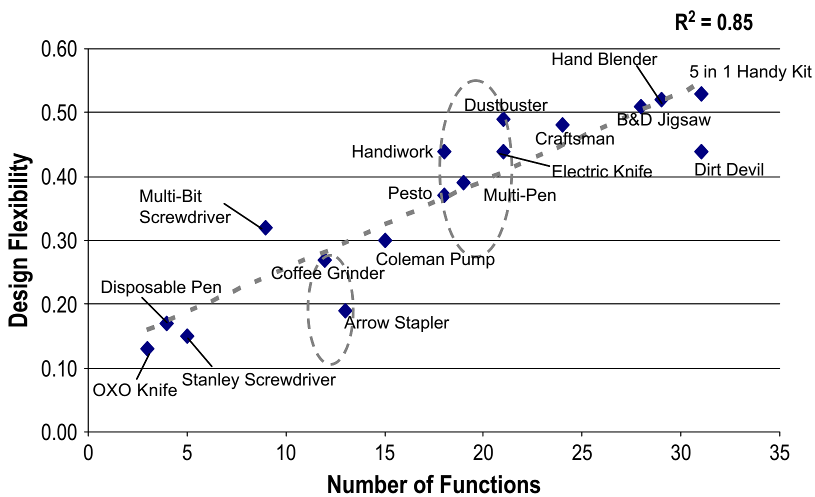

Figure 8 Design flexibility vs. number of functions

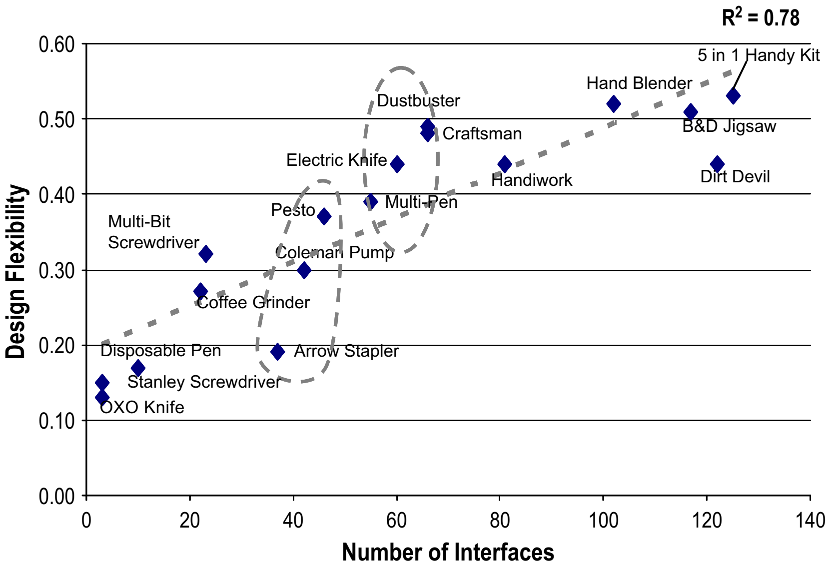

Figure 9 Design flexibility vs. number of interfaces

graphs, we observe that as the number of parts, functions and interfaces in a product increases, the design flexibility increases. Figure 10 shows that there is a strong correlation between the number of modules and design flexibility (F). This graph strongly suggests that design flexibility

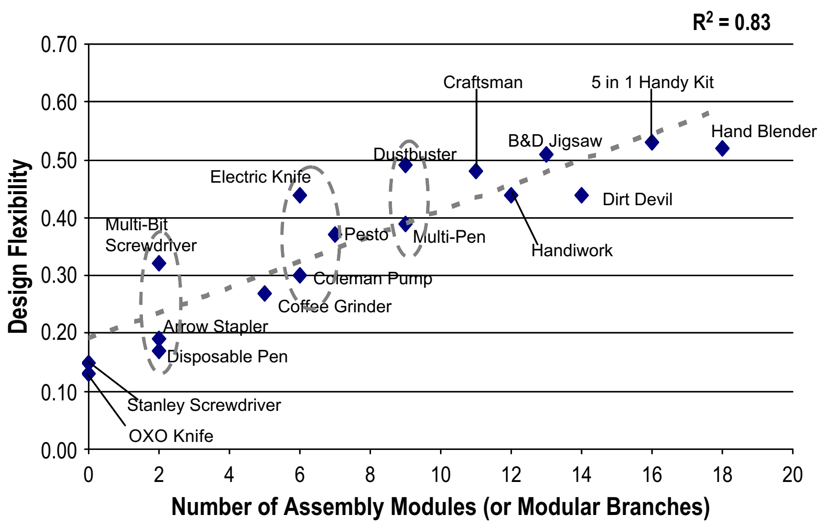

Figure 10 Design flexibility vs. number of assembly modules

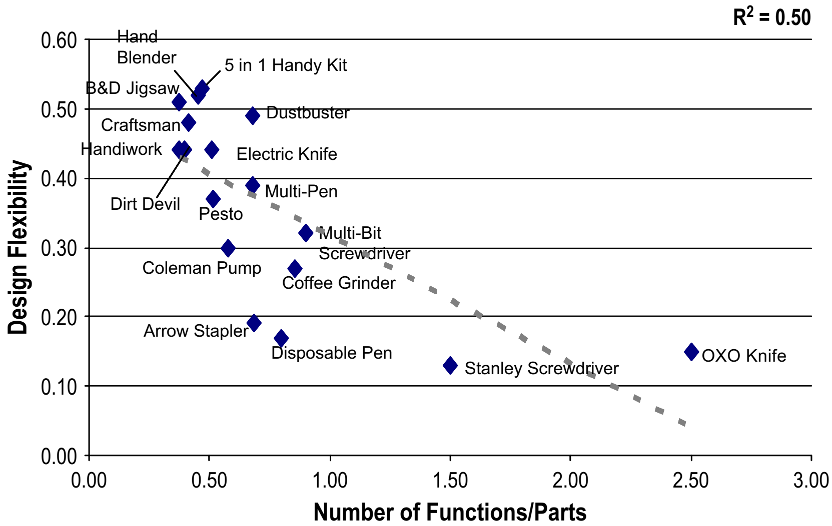

Figure 11 Design flexibility vs. number of functions/parts

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 7—10, 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.

Conversely in Figure 11, the ratio of the number of functions to the number of parts is inversely proportional to the design flexibility. This weak overall trend suggests that as the design is more integrated (i.e. integral), 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.

In order to investigate the issue of how the modules interact in the design, we plot the ratio of the number of inter-modular interfaces to number of interfaces with design flexibility. We find in Figure 12 that because the data forms such a sparse pattern, there is only a weak trend suggesting that as the ratio of inter-modular interfaces to interfaces increases, the design flexibility (F) increases.

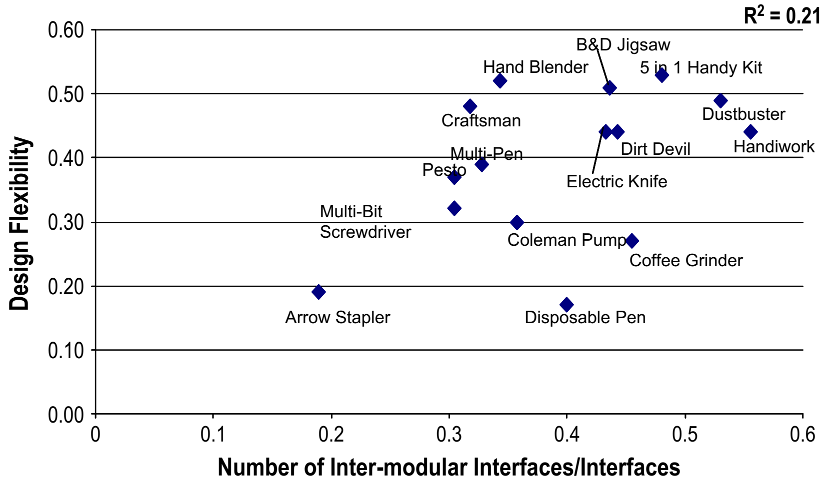

Figure 12 Design flexibility vs. number of inter-modular interfaces/interfaces

Figure 13 is a plot between the ratio of the number of assembly modules to parts with flexibility. 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 it means that increasing or decreasing the number of parts in a module does not affect flexibility. This is intuitively

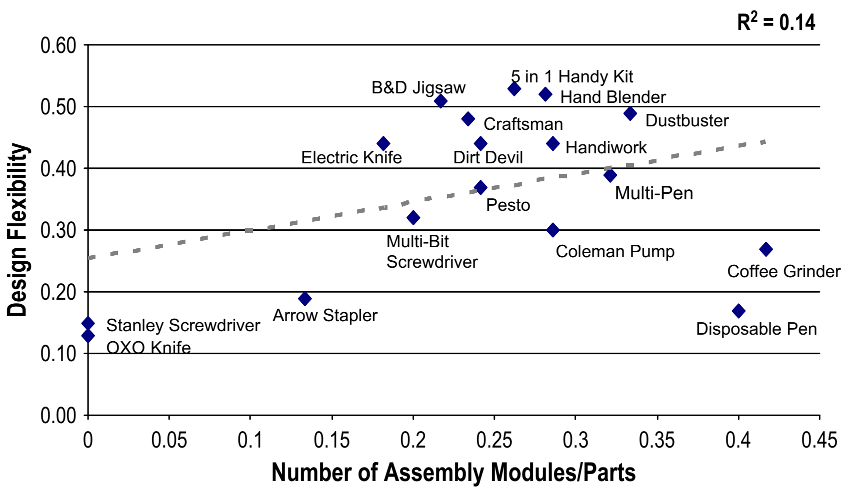

Figure 13 Design flexibility vs. number of assembly modules/parts

reasonable, since aggregation is the opposite of partitioning, and so the effects seem to cancel out. On the surface, it may seem to contradict Figure 7, which shows that reduced number of overall parts will lead to a reduction in flexibility. However, the reader should carefully note that Figure 13 suggests that 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 7–9, we observe roughly horizontal regions where significant differences exist in the design flexibility (F) rating, while little differences exist 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. When observing Figure 10 with respect to these horizontal regions, we find that these products do not present a significant difference in their number of modules. For example in Figures 7–9 consider the horizontal region, which consists of the Dustbuster, B&D 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 10, 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 12, which is a plot between the ratio of the number of inter-modular interfaces to interfaces with design flexibility (F). When we observe the Dustbuster and Multi-Pen, the former has a greater number of inter-modular interfaces. Similar results can be observed with other groups of products, which are highlighted in Figures 7–10. However, based on observations of DSM and physical products, it appears that most of these modules in more flexible products (Dustbuster, B&D Electric Knife & Multi-Bit Screwdriver) are external attachments. Alternatively, most of the modules in the less flexible products (Arrow Stapler, Coleman Pump and Papermate Multi-Pen) are enclosed inside the housing. This can be observed in Figures 14 and 15, where the Dustbuster is more flexible and has more number of external modular attachments, when compared to Multi-Pen.

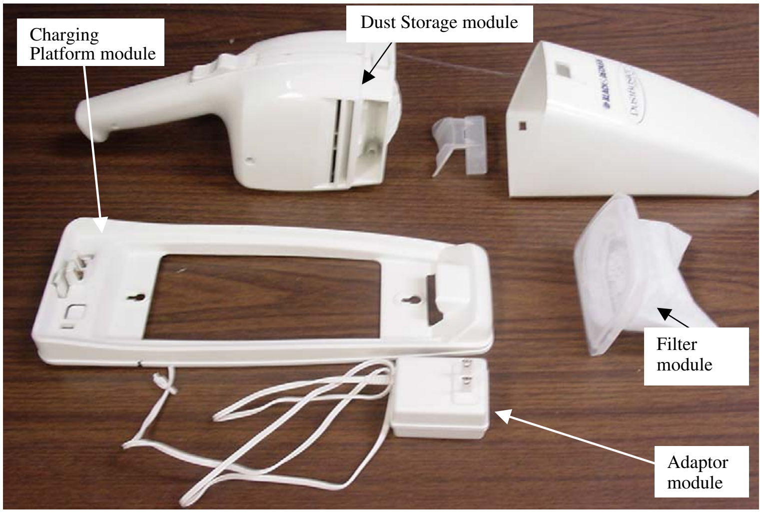

Figure 14 Dustbuster Cordless Vacuum (B&D) DB250C

Figure 16 presents 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 Jig Saw had large numbers of OEM parts, they did not have a proportional increase in their flexibility. When observing these physical products, and during the change modes and effects analysis, it was found that most of these OEM parts 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

Figure 15 Papermate Multi-Pen

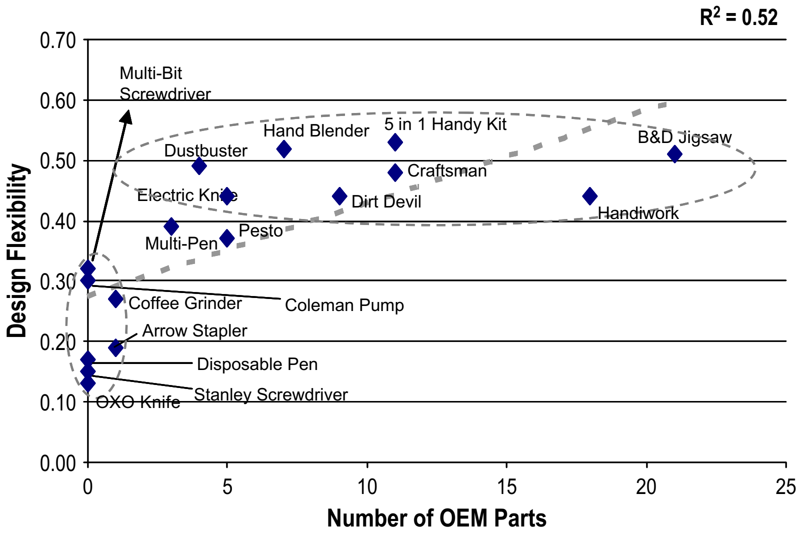

Figure 16 Design flexibility vs. number of OEM parts

the insight that having 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.

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 are plotted with respect to the number of parts. Figures 18–20 show the correlation between the physical parameters like number of parts, functions, modules, and interfaces. We observe a strong correlation

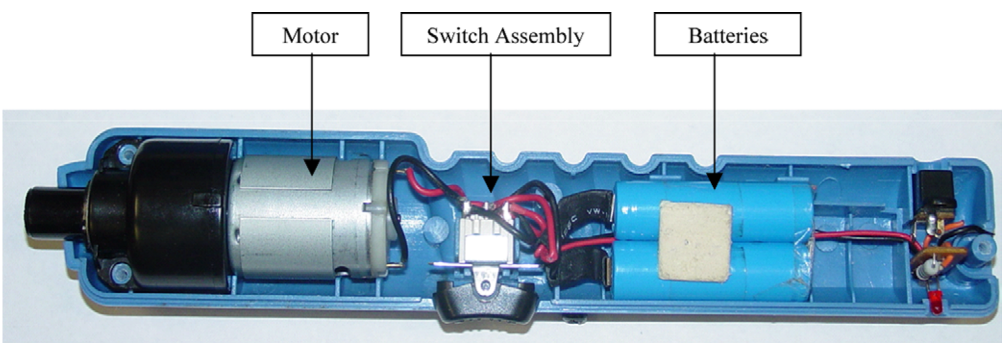

Figure 17 Handiwork Screwdriver with housing removed

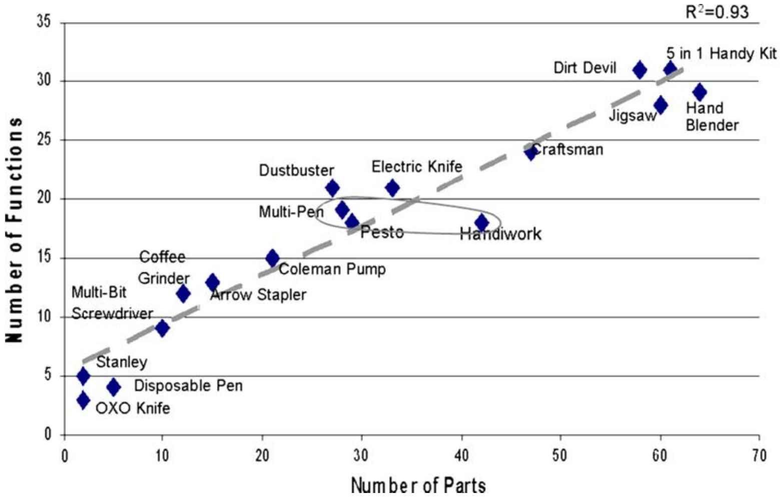

Figure 18 Number of parts vs. number of functions

between them. The general trend in Figure 18 shows the increase in part count to achieve the added functionality in the products. Figures 19 and 20 are consistent with VanWie's (Wan Wie, et al., 2001) empirical results. In Figure 20, the general trend suggests the implementation of a modular strategy for 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 useful is to study products, where the number

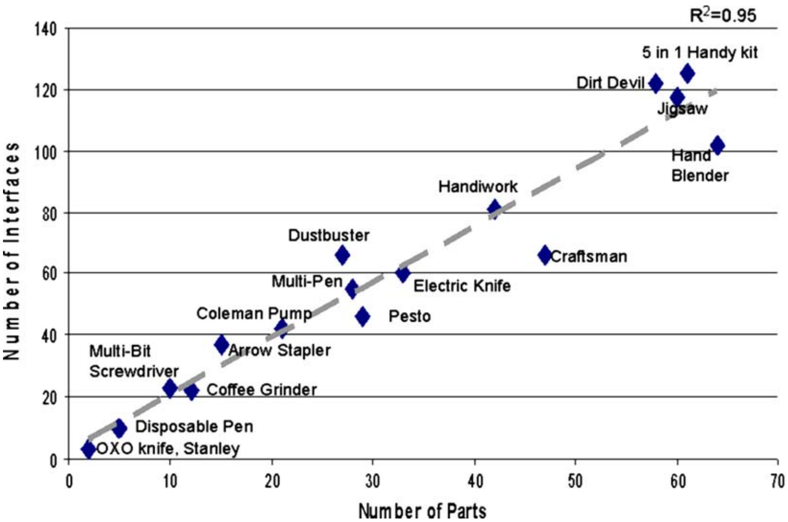

Figure 19 Number of parts vs. number of interfaces

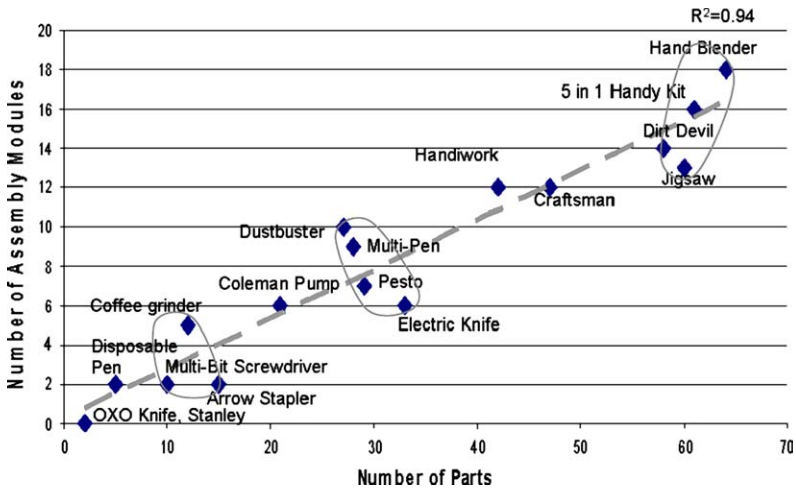

Figure 20 Number of parts vs. number of assembly modules

of parts is not directly proportional to the number of functions or modules or interfaces.

5 *Conclusions and discussion*

The overall objective of this work is to understand the issue of flexibility and to develop a method for evaluating product flexibility. The CMEA method is developed, based on FMEA, and is found to be a reasonable indicator of product flexibility based on a limited validation study. Given this new CMEA method, we are able to find several relations of various physical parameters with flexibility. We show through an empirical evaluation of 17 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. Several conclusions from this study are summarized as guidelines as follows:

a) Modularizing the design leads to more product flexibility. As the design becomes more integrated, it becomes more inflexible for redesign.
b) Designing the modules in a product, as external attachments, makes the design even more flexible.
c) Designing with more standard components and interfaces will improve product flexibility.
d) Directed partitioning of a design into a greater number of elements (manifested through higher numbers of components and functions) improves the flexibility.

e) 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 to have simultaneous design for improved assemblability, while maintaining flexibility.
f) With the help of these guidelines, the designer can exercise and focus their efforts to better control the flexibility of a design.

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 issues. In terms of end users, this technique is a formal and systematic way of documenting and considering 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 should lead to lower redesign costs. 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 a company to identify opportunities and find 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 generally not readily available. These limitations might make this method a more time intensive effort 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. For more accurate results, designers should brainstorm all possible ways a component may change in future renditions of the product and record the results within a CMEA table. Outside of this case-by-case time intensive process, we have discovered a few general trends that seem to be independent of a product's operations and complexity.

6 *Future work*

The following discussion addresses extensions of the current work and highlights ongoing problems that will likely require substantial further effort. 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. 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. Some departure points for future work are to further understand the correlation of the different physical factors in a product, like number of parts, functions, modules, interfaces and type of interfaces, with respect to flexibility. Although an initial effort is taken towards this direction, an extensive empirical study on numerous products across different domains could be done. While this effort will be more time and cost consuming, a significant contribution from this work would likely lead to the determination of more guidelines, and further clarification of existing guidelines.

The work presented here is more oriented towards understanding flexibility in the later stages of the design process, namely the configuration and embodiment stages. A next step is to understand flexibility in the functional stages of product design. When considering this approach, some interesting questions arise. Is there a set of functions in a functional model, which can enhance flexibility in a product? Can some functions or group of functions, connected with certain flows, affect the flexibility of product architecture?

One of the significant future extensions of this work would be to develop a comprehensive methodology to 'Design for Flexibility'. This would be an important contribution to design theory in general. Such a methodology will focus on a systematic step-by-step procedure of designing the product to a desired level of flexibility. Given the complexity of this problem and based on the understanding of flexibility in this research, this will require a significant effort.

References

Benjamin, S B and Wolter, J F (1998) Systems engineering and analysis *International Series in Industrial and Systems Engineering*, Prentice Hall, NJ, USA

Brown, J, Dubois, D, Rathmill, K, Sethi, S P and Stecke, K E (April 1984) Classification of flexible manufacturing systems *The FMS Magazine*

Gerwin, D (March–April 1982) Do's and don'ts of computerized manufacturing *Harvard Business Review* Vol 60 pp 107–116

Gerwin, D (1987) An agenda for research on the flexibility of manufacturing processes *International Journal of Operations and Production Management* Vol 7 No 1 pp 38–49

Jaikumar, R (November–December 1986) Postindustrial manufacturing *Harvard Business Review* Vol 64 pp 69–76

Mc Adams, D A, Stone, R B and 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* Prentice Hall, New Jersey, USA

Palani Rajan, P K (2003) Design for flexibility – measures and guidelines *Thesis*, University of Texas at Austin

Palani Rajan, P K, Van Wie, M, Otto, K and Wood, K (2003) Matthew I. Campbell design for flexibility – measures and guidelines *International Conference on Engineering Design*

Sethi, A K and Sethi, S P (1990) Flexibility in manufacturing: a survey *International Journal of Flexible Manufacturing Systems* Vol 2 No 4 pp 289–328

Son, Y K and Park, C S (1987) Economic measure of productivity, quality and flexibility in advanced manufacturing systems *Journal of Manufacturing Systems* Vol 6 No 3 pp 193–207

Sosa, M E, Eppinger, S D and Rowles, C M (2000) Designing modular and integrative systems *ASME Design Engineering Technical Conference Proceedings*, DETC00/DTM-14571

Stone, R B and Wood, K L (1999) Development of a functional basis for design *ASME Design Engineering Technical Conference Proceedings*, DETC99/DTM-8765

Stone, R B and Wood, K L (December 2000) Development of a functional basis for design *Journal of Mechanical Design* Vol 122 pp 359–370

Van Wie, M (2002) Designing product architecture – a systematic method *Dissertation*, University of Texas at Austin

Van Wie, M, Greer, J, Campbell, M, Stone, R and Wood, K (2001) Interfaces and product architecture *ASME Design Engineering Technical Conference Proceedings*, DETC00/DTM-21689