A PRODUCT ARCHITECTURE-BASED CONCEPTUAL DFA TECHNIQUE

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A conceptual Design for Assembly (DFA) method is introduced in this paper. The method incorporates DFA analysis into the conceptual design phase. Current DFA methods, essentially all of which are post design DFA analyses, are reviewed with emphasis on the popular Boothroyd and Dewhurst method. The product architecture-based conceptual DFA method uses two relatively new concepts: the functional basis and the method of module heuristics. The functional basis is used to derive a functional model of a product in a standard language and the module heuristics are applied to the functional model to identify a modular product architecture. The number of modules identified represents the theoretical minimum number of parts for a product. The embodiment or form definition phase then attempts to solve each module with one part (or as few as possible). The critical advantage of the conceptual DFA method is that it does not require a physical prototype or completed design geometry, thus reducing the number of design iterations before seeing DFA benefits. One case study compares the conceptual DFA method with the Boothroyd and Dewhurst DFA method and shows their equivalence in part count reduction. A second case study examines the evolution of products over the years. This study reveals the evolution of products into designs with smaller part counts, closely matching the modules identified by the conceptual DFA method. This lends credence to the method proposed in this paper as a useful tool for reducing the design cycle time.

Design for assembly (DFA) analyzes product designs to improve assembly ease and reduce assembly time. Often this is accomplished through a reduction in part count. The implementation of DFA techniques has played an important role in reducing costs of manufacturing over the last two decades. It is apparent that for both manual and automated assembly, the effective methods to reduce assembly costs were those applied during design; manufacturing and production changes have less impact on product cost. The majority of commercial DFA methodologies developed in the last 15 years are applicable only during the embodiment design phase. The ability to apply DFA analysis at the conceptual design stage has been neglected. As a result, the DFA methods then force another iteration on the design, thus consuming time, material, and financial resources.

We present in this paper a product architecture-based approach to DFA analysis which may be applied in the conceptual design stage. The necessary input to this analysis is a well-refined function structure of the product, i.e. no form information is required. Applying a heuristic method to define modular product architectures, modules are identified from the function structure of the product. The modules, identified as groups of sub-functions, indicate the theoretical minimum number of parts and, thus, guide the form solution toward that goal.

The rest of this article consists of a review and categorization of the current state of the art in DFA; the presentation and development of a novel product architecture-based approach including a detailed application method; and two case studies. The case studies clarify the application of the method, show the utility of the product architecture DFA method, and allow the exploration between product evolution and the results of applying this research presented in this article.

1 A REVIEW OF THE STATE OF DFA TECHNIQUES

1.1 Attributes of DFA Techniques

Design For Assembly addresses assembly quality largely through product structure simplification and reduction in the total numbers of parts in a product. Redford and Chal (1994) state that any DFA method should have the following features: 1) It should be a complete method as regards to procedures for evaluating assemblability and should be creative enough to obtain procedures for improving assemblability. 2) It should be a systematic step-by-step procedure, which considers all relevant issues. 3) It should be able to measure assemblability objectively, accurately and completely. 4) It should be user friendly and should have good quality.

Current DFA methodologies can be classified into four basic types based on their analysis method. The four types are described in the following subsections.

1.1.1 DFA systems using design principles and design rules:

1) Design rules are empirical "truths" verified by extensive design practice. Andreasen (1985) and Weissmantel (Redford and Chal, 1994) have framed rules, which help in this type of DFA method. Suh (1988) proposes two basic axioms for design with corollaries. The basic axioms are: 1) maintain the independence of functional requirements; and 2) minimize the information content. Some of the corollaries include using standardized or interchangeable parts whenever possible, conserving materials and energy or reducing the number of parts.

1.1.2 DFA systems employing quantitative evaluation procedures:

Quantitative DFA analysis allows designers to rate the assemblability of their product designs quantitatively. Quantitative measures allow a more accurate and repeatable application of DFA methods. Using current quantitative approaches, the designer has to determine the assembly process operation by operation. Each assembly operation is subject to a rating that assesses the ease with which operators or assembly systems carry out the process. There are several quantitative evaluation methods like Hitachi's Assembly Evaluation Method (AEM) (Ohashi, 1985 and Suzuki, 2001), the Boothroyd-Dewhurst method (Boothroyd, 1992), the Xerox Producibility Index (Lewis, 1985; Waterbury, 1986) or assembly trees (Ishii, 1994). Extensions to such methods include the subtract-operate procedure and force flow analysis for piece count reduction in a product (Lefever and Wood, 1996). The most popular method of this category is the Boothroyd and Dewhurst method, which is discussed separately in this paper.

1.1.3 DFA methods employing knowledge based approaches:

Knowledge based systems are defined as those that provide new information processing capabilities such as inference, knowledge based management or search mechanisms combined with conventional computer capabilities.

1.1.4 Computer aided DFA methods:

In this category, assemblability evaluation processes are being developed by which DFA systems are integrated with CAD. Assemblability data are extracted from 3-D CAD models using feature processing. The part model can give useful data for the assemblability evaluation such as shape symmetry and center of mass. The Lucas method is a good example of this type of DFA approach (Swift, 1989).

1.2 Boothroyd and Dewhurst Method

Boothroyd and Dewhurst (1994) have formulated one of the most widely recognized DFA methodologies. In their method, the DFA analysis focuses on redesigning an existing product through a two step procedure applied to each part in the assembly. The first step evaluates each part to determine if it is necessary or a candidate for elimination or combination with other parts in the assembly. The second step estimates the time taken to grasp, manipulate and insert the part during assembly. Execution of the two steps allows a design efficiency rating to be calculated and used to compare different designs. The procedure for analyzing manually assembled products is summarized as follows:

1) Obtain the best information of the product or assembly through items such as engineering drawings, a prototype or an existing product.
2) The product is disassembled and an identification number is assigned to each item as it is removed.
3) The product is reassembled. The part with the highest identification number is added to the work fixture and the remaining parts are added one after the another.

4) During the assembly, a worksheet is completed to compute the theoretical part number and assembly time. A sample worksheet is shown in Figure 1.

In Fig. 1, column (3) contains the two-digit handling process code selected from the manual-handling chart. The handling process code is determined from a sophisticated classification scheme that incorporates knowledge of how the part is held and oriented in the assembly operation. For instance, handling is classified based on whether the part is held with one hand, one hand with grasping aids, two hands for manipulation, or two hands due to large size. Orientation is classified with respect to rotational symmetry of a part about the axis perpendicular to the axis of insertion denoted by α and about the axis of insertion denoted by β, and the size and thickness of the part. Column (4) contains the handling time in seconds, obtained from the chart for the corresponding handling code. Column (5) contains the insertion process code obtained from the manual insertion chart and column (6) contains the corresponding insertion time in seconds. Column (7) is the calculation of the total operation time. Total operation time is the sum of the handling and insertion times in columns (4) and (6) multiplied by the number of operations in column (2).

1	2	3	4	5	6	7	8	9
Part No	No. of operation	Manual handling code	Manual handling time (s)	Insertion code	Insertion time (s)	Total operation time (s)	Theoretical minimum no. of parts	Part name
1	1	30	1.95	00	1.5	3.45	1	Plastic support
2	1	30	1.95	30	2.0	3.95	0	Hammer guide
3	1	23	2.36	30	2.0	4.36	1	Hammer

Figure 1 A worksheet fragment used in the Boothroyd and Dewhurst DFA analysis of a product.

Column (8) contains the theoretical minimum number of parts for the assembly which is determined by answering the following three questions:

a) During operation of the product, does the part move relative to all other parts already assembled.

b) Must the part be of a different material than, or be isolated from all other parts already assembled.

c) Must the part be separate from all other parts already assembled because otherwise necessary assembly or disassembly of other parts would be impossible?

If the answer is "yes" to any of the above questions for a part, then a '1' is placed in column (8). Finally the manual assembly design efficiency is obtained by use of the formula

$$EM = 3 \cdot (NM/TM)$$

where EM is the manual design efficiency, NM is the theoretical minimum number of parts and TM is the total manual assembly time.

The Boothroyd and Dewhurst method has a useful tool to reduce overall assembly time. Review of the worksheet in Figure 1 reveals the difficulty in applying the Boothroyd and Dewhurst method during conceptual design. The method requires an existing product or detailed and almost finalized design. As noted by Redford and Chal (1994), a key advance in DFA analysis would be to enable such analysis earlier in the design process

2 A PRODUCT ARCHITECTURE-BASED APPROACH TO DFA

Our product architecture-based approach to DFA is shown in Figure 2. This approach moves the DFA analysis to the early stages of conceptual design requiring only a functional model for implementation. Briefly, the approach is as follows. Through a product architecture definition method, the function structure of a product is clustered into modules. The number of modules represents the theoretical minimum number of parts for the product. The modules then guide the form definition step, focusing the design efforts on creating the minimum part count product. During the form definition, Boothroyd and Dewhurst handling time information may be used to minimize the assembly time and cost. The end product of the design process is a detailed design for which design for assembly principles have continuously been applied. Thus, design for assembly is realized with a substantial saving in time and overall effort.

Steps 1 and 4 of the conceptual design phase shown in Fig. 2 are not discussed in detail here as there are many references which describe their application (Pahl and Beitz, 1996;

Ullman, 1997; Ulrich and Eppinger, 1995; Cutherell 1996; Otto and Wood, 1997; Stone *et al.*, 1999). The modified functional derivation step (Step 2) and the new step of defining product architecture (Step 3) are discussed in the next sections.

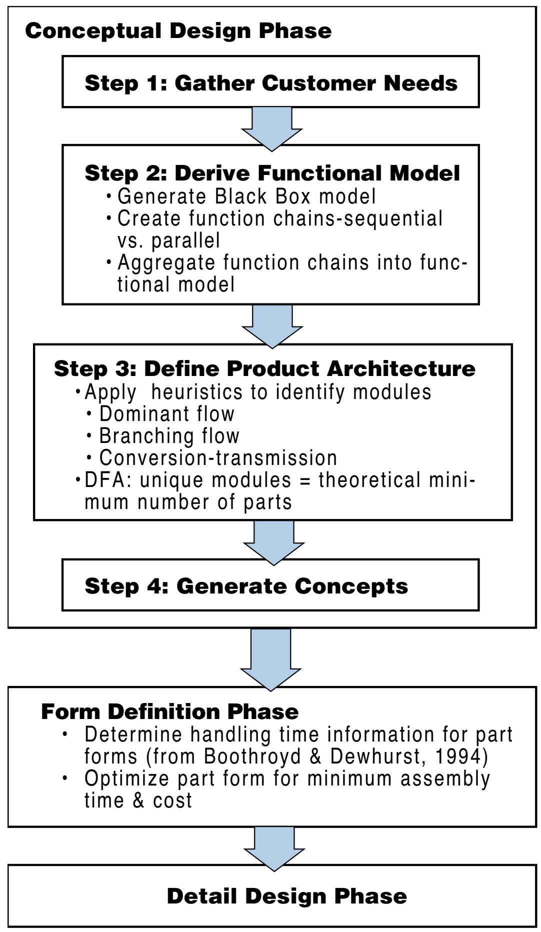


Figure 2 The product architecture-based approach to DFA.

2.1 Functional Model Derivation

Functional modeling consists of formulating the overall function of a product as a combination of smaller, more elemental sub-functions. The overall function is the ability of a product to transform a set of input flows into a desired output flow or a set of flows. By decomposing the overall function of the product into small easily solved sub-functions the form of the device follows from the assembly of all sub-function solutions. Functional models are most commonly expressed as a function structure which consists of sub-functions described by a verb-object pair and connected into a structure by the flows on which they operate. The function structures are expressed in terms of a common vocabulary known as the functional basis (Hirtz *et al*., 2002; Stone and Wood, 2000; Little *et al*., 1997; Otto and Wood, 1997). It is a set of functions and flows capable of defining the entire mechanical design space. Functions are divided into eight classes with further divisions listed as basic functions and shown in Table 1. Flows are divided into three classes and, similarly, further specified as basic flows and shown in Table 2. The basis functions fill the verb spot and the basis flows provide the object of the sub-function description. The result of this step is a function structure of a product expressed in a common language.

Table 1. Function classes and their basic categorizations.

Class	Branch	Channel	Connect	Control	Convert	Provision	Signal	Support
Secondary (or Basic)	Separate Distribute	Import Export Transfer Guide	Couple Mix	Actuate Regulate Change Stop	Convert	Store Supply	Sense Indicate Process	Stabilize Secure Position

Table 2. Flow classes and their basic categorizations.

Class	Material	Signal	Energy		
Secondary (or Basic)	Human Gas Liquid Solid Plasma Mixture	Status Signal	Human Acoustic Biological Chemical	Electrical Electromagnetic Hydraulic Magnetic	Mechanical Pneumatic Radioactive Thermal

2.2 Product Architecture Definition and DFA

With a function structure expressed in the common language of the functional basis, sub-functions are clustered to define modular product architecture. We postulate that the number of modules defined in a function structure indicates the theoretical minimum number of parts for the product, thus integrating DFA analysis into the conceptual design phase. This step is modified from the product architecture definition method first proposed by Stone *et al.* (1998 & 1999) and utilized in product architecture research (Gonzalez-Zugasti, 2000 and Siddique, 2001).

Stone et al. (1998) develop a set of three heuristics to identify theoretically potential modules. The method requires only a functional model. The heuristics require a functional model in the form of a function structure, where sub-functions are then clustered based on flow (energy, material, or signal) relationships. The three heuristic are stated below and shown schematically in Figures 3 - 5

Dominant-Flow Heuristic: The set of sub-functions which a flow passes through, from entry or initiation of the flow in the system to exit from the system or conversion of the flow within the system, define a module.

Branching Flow Heuristic: Parallel function chains associated with a flow that branches constitute modules. Each of the modules interfaces with the remainder of the product through the flow at the branch location.

Convert-Transmit Heuristic: A conversion sub-function or a conversion-transmission pair or proper chain of sub-functions constitutes a module.

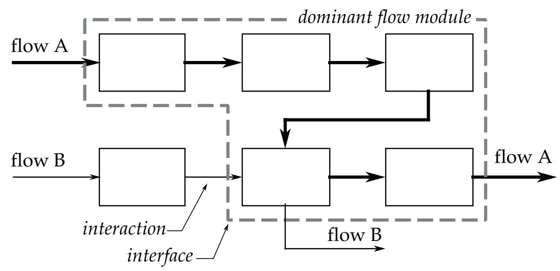


Figure 3. Dominant flow heuristic applied to a generic function structure.

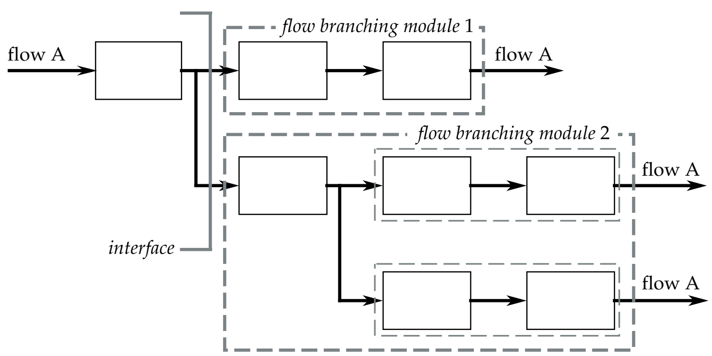


Figure 4. Flow branching heuristic applied to a generic function structure.

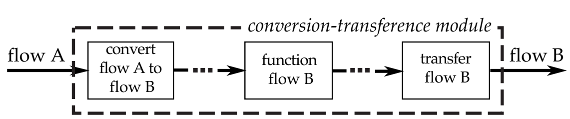


Figure 5. Conversion-transmission applied to a generic set of sub-functions.

Application of the three heuristics generates a set of possible modules for a product. This set may not consist of unique modules. In other words, the heuristics may recommend two modules which cannot simultaneously exist in the product. In this case, design judgment must be exercised to select a particular and unique set of product modules. Often, choosing the module with the fewest number of flow interactions crossing the module boundary produces a simpler modular structure.

2.3 Modular Concept Generation

The unique set of modules defines the theoretical minimum number of parts for the product and guides the form definition phase to embody the module with as few parts as possible, ideally with a single part. As solutions to the product are generated, modules are solved in their entirety rather then sub-function by sub-function. By focusing on one-piece or minimal piece solutions to modules (i.e., groups of sub-functions that are closely related), the designer is taking assembly considerations into account at the conceptual level.

3 CASE STUDIES

Our hypothesis is that a product architecture-based technique can move DFA analysis to the conceptual design stage and produce minimal part count products similar to other post-design DFA techniques. Case studies of existing products provide perhaps the only way to validate our claim. The results that follow illustrate two major benefits of the product architecture-based DFA technique. The first is that conceptual DFA analysis leads to minimal part count products that are essentially equivalent to those resulting from a post-design DFA analysis such as Boothroyd and Dewhurst. The second benefit demonstrates the potential design cycle savings that can be achieved when a conceptual DFA analysis is executed.

3.1 Comparing Theoretical Minimum Number of Parts

Here we compare the theoretical minimum number of parts that a conceptual (the product architecture-based method of Section 3) and post-design (Boothroyd and Dewhurst) DFA analysis identify. Two products, a heavy-duty stapler and an electric wok, are considered in the following two case studies.

Case study 1: Heavy duty stapler

Post-design DFA Analysis. The heavy duty stapler considered here is shown in Fig. 6. First, the Boothroyd and Dewhurst analysis for stapler is completed and shown in Fig. 7.

Figure 6 The heavy duty stapler used in case study 1.

1	2	3	4	5	6	7	8	9
Part No	No. of operation	Manual handling code	Manual handling time (s)	Insertion code	Insertion time (s)	Total operation time (s)	Theoretical minimum parts	Part name
1	1	30	1.95	00	1.5	3.45	1	Plastic support
2	1	30	1.95	30	2.0	3.95	0	Hammer guide
3	1	23	2.36	30	2.0	4.36	1	Hammer
4	1	30	1.95	06	5.5	7.45	1	Stapler advance mechanism
5	1	33	2.51	06	5.5	8.01	1	Left Casing
6	2	15	2.25	03	3.5	11.5	0	Rivet
7	1	10	1.5	31	5.0	6.5	1	Bottom Leaf Spring
8	1	10	1.5	00	1.5	3.0	0	Top leaf spring
9	1	33	2.51	01	2.5	5.01	1	Left lifter
10	1	00	1.13	06	5.5	6.63	1	Plastic pin
11	1	33	2.51	01	2.5	5.01	1	Right lifter
12	1	30	1.95	07	6.5	8.45	1	Plastic Handle
13	1	30	1.95	30	2.0	3.95	0	Metal handle
14	1	15	2.25	30	2.0	4.25	1	Pin
15	1	15	2.25	30	2.0	4.25	0	Stud
16	2	30	1.95	06	5.5	14.9	0	Lifter cover
17	1	30	1.95	06	5.5	7.45	0	Spring mount
18	2	05	1.84	06	5.5	14.68	2	Springs
19	1	34	3.0	06	5.5	8.5	0	Metal spring holder
20	1	33	2.51	06	5.5	8.01	1	Right casing
21	1	15	2.25	38	6.0	8.25	0	Pin
22	1	39	4.0	31	5.0	9.0	0	Circlip

23	2	-	-	35	7.0	14.0	0	Riveting operation for rivet in row 6
24	1	33	2.51	08	6.5	9.01	0	Front casing
25	1	15	2.25	38	6.0	8.25	0	Pin
26	1	39	4.0	31	5.0	9.0	0	Circlip
27	1	23	2.36	31	5.0	7.36	1	Locking pin
					Totals	204.18	14	
Total number of parts is 29 The manual design efficiency is given by EM = 3 X 14/204.18 = 20.60 %								

Figure 7 Boothroyd and Dewhurst assembly worksheet for a heavy duty stapler.

The assembly sequence shown here is derived from the reverse order of steps for disassembly. The operation cost is not taken into consideration in this analysis. A "0" in column (8) indicates that, theoretically, the part is not essential to the assembly.

The analysis suggests several changes to the design, which can be implemented if the manufacturing cost for the change is justifiable. These changes are enumerated below.

a) The hammer guide (part 2) could be combined with the plastic support (part 1).

b) The casings (parts 5 & 20) could be attached by snap fits to the plastic support (part 1)

c) The two leaf springs (parts 7 & 8) could be combined as one leaf spring with the same weight.

d) Providing slots in the plastic pin (part 10) could eliminate the lifter cover (part 16)

e) The metal spring holder (part 19) could be combined with the handle assembly (part 13)

f) The spring mount (part 17) could be integrated with the casings (parts 5&20).

Thus there is a reduction to 14 parts from the original 29 parts of the existing model. The assembly time will also decrease with decreasing number of parts. The manual design efficiency of the revised design is EM = 3 X 14/89.17 = 47.1%, where 14 is the reduced number of parts and 89.17 is the sum of the operation time of the parts which have '1' in their theoretical minimum number of parts.

Conceptual DFA Analysis. Now we apply the product architecture-based conceptual DFA method to the stapler. A function structure for the heavy-duty stapler is developed following step 2 of our conceptual DFA methodology and the reverse engineering methodology of Otto and Wood (1996). Note that an existing product is not necessary for our conceptual DFA analysis in general, but necessary for our comparison with other post-design DFA techniques.

The stapler function structure is shown in Fig. 9. Material flows include *hand*, *staples* and *sheet* to be stapled as input and *hand* and *stapled sheet* as output. Energy flows include *human force* as input and *sound* as output. Signal flows include the *staples empty/full* status and the *size of staples* status. The flows are operated on by the stapler and expressed as sub-functions. Applying the module heuristics (step 3) identifies six modules: staple, rotation-translation 1, rotation-translation 2, grip, pin and lock. Note that both rotation-translation modules contain a sub-module that deals only with their translational flows. However, the subsuming conversion-transmission heuristic is identified here as it leads to the minimal number of modules. Additionally, the flow *rotation 1* represents the main energy used for the staple action while the flow *rotation 2* is an auxiliary energy flow used to return the handle to its starting position.

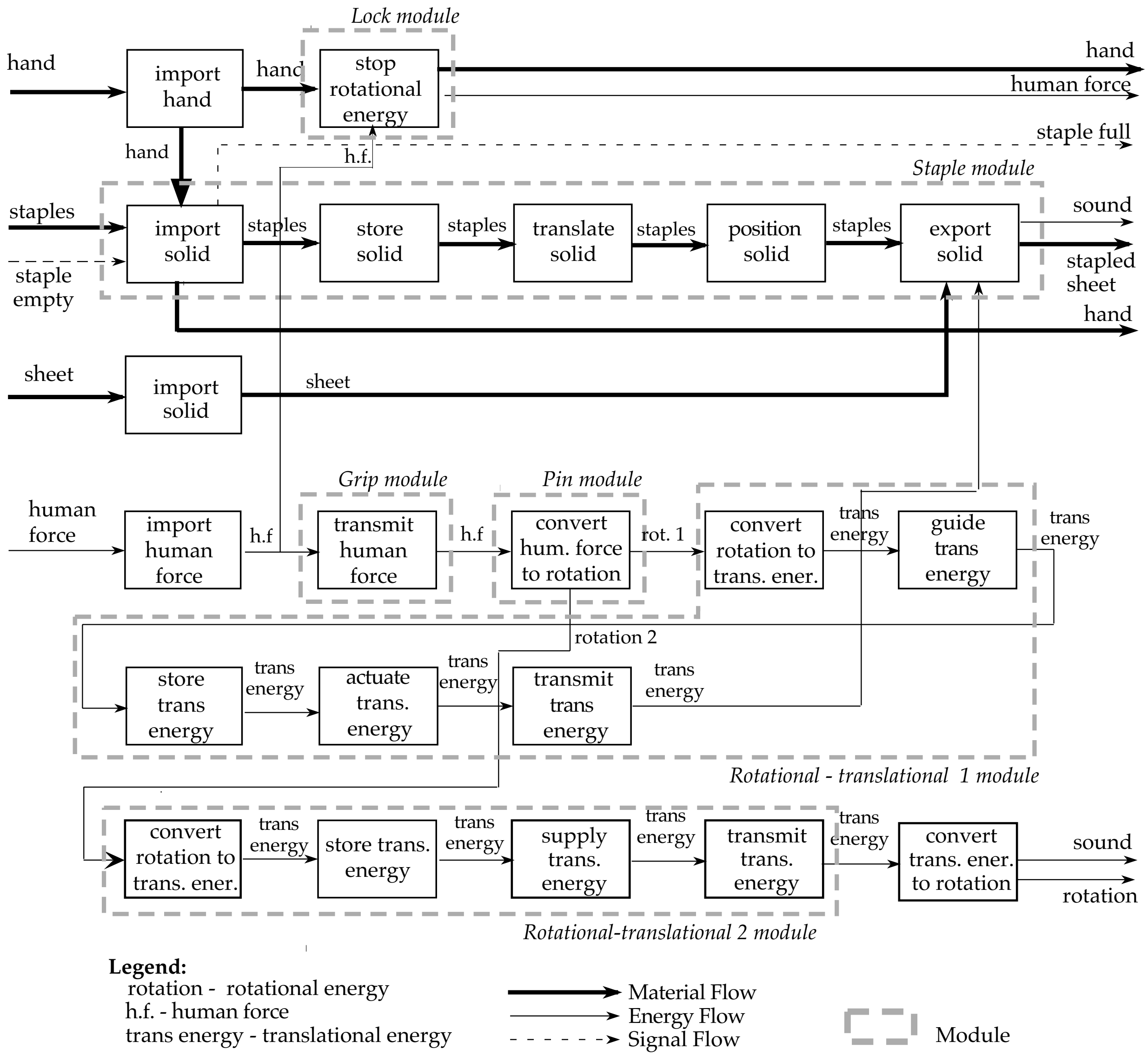


Figure 9 The function structure of a heavy duty stapler with modules identified.

The six modules in Fig. 9 represent the theoretical minimum number of parts for the staple gun if the functionality of each model can be solved by one part. As with the Boothroyd and Dewhurst theoretical minimum, there are physical possibilities that preclude this theoretical ideal from being achieved. Nevertheless, using the one module – one part ideal as a goal, a concept is developed. The proposed conceptual design of the stapler is shown in Fig. 10. The module to part count comparison for the existing stapler and the conceptual stapler (based on the six modules) is shown in Fig. 11.

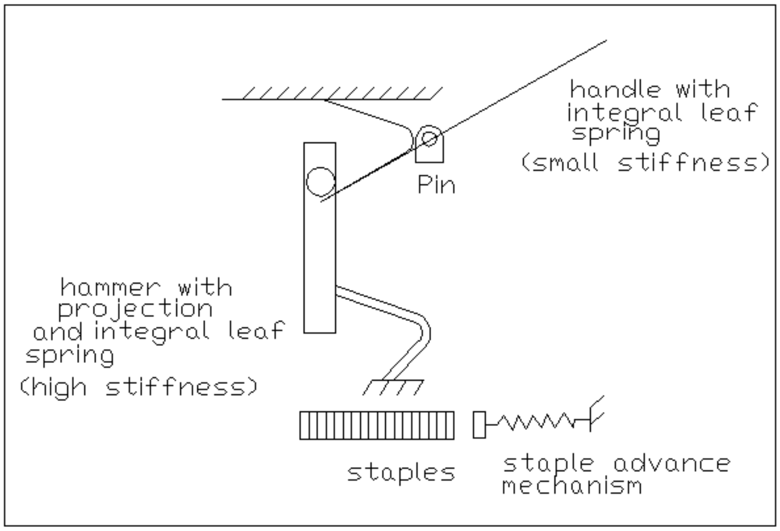


Figure 10 Form given to the modules proposed by conceptual DFA method.

Module	Existing Design Component descriptions	Part count	Time	Proposed Concept Component descriptions	Part count	Time
Staple	Plastic support Staple advance mechanism	1 1	3.45 7.45	Staple advance mechanism Casings	1 2	7.45 16.02
Rotation-translation 1	Metal handle Leaf springs Hammer Hammer guide Left lifter Right lifter Plastic pin Front casing Stud Lifter covers	1 2 1 1 1 1 1 1 1 2	3.95 9.5 4.36 3.95 5.01 5.01 6.63 9.01 4.25 14.9	Hammer with integral leaf spring and projections	1	6.0
Rotation-translation 2	Springs Spring mount Metal spring holder Casings	2 1 1 2	14.68 7.45 8.5 16.02	Handle with integral leaf spring	1	14.0
Grip	Plastic handle	1	8.45	Handle with integral leaf spring Casings	0 0	
Pin	Pin	1	4.25	Pin	1	4.25
Lock	Locking pin	1	7.36	Locking Pin	1	7.36
Other parts	Rivets and riveting Pins Circlips	2 2 2	25.5 16.5 18.0	Screws	4	33.0
		29	204.18		11	88.08

Figure 11 Module to part count comparison of the existing and proposed design of the stapler.

Figure 11 identifies components for the modules in the existing model and the proposed concept model. There are 29 parts in the existing design, which can be assigned to the modules identified from Fig. 9. The assembly time is 204.18 seconds. For the proposed concept model there are 11 parts and assembly time is 88.08 seconds.

Summary. Both methods lead to part count reduction. The Boothroyd and Dewhurst method gives a theoretical minimum of 14 parts while the product architecture-based method gives a theoretical minimum of 6 parts with am embodied minimum of 11. The two methods both enable the designer to reduce part count and assembly cost. The key distinction and advantage of the conceptual DFA technique is that it is not a redesign method like that of Boothroyd and Dewhurst. The conceptual DFA method allows the designer to concurrently consider Design for Assembly principles during concept generation.

Case study 2: Electric wok

Post-design DFA Analysis. The electric wok considered here is shown in Fig. 12. First, the Boothroyd and Dewhurst analysis for the wok is completed and shown in Fig. 13.

Figure 12 The electric wok used in case study 2.

1	2	3	4	5	6	7	8	9
Part No	No. of operation	Manual handling code	Manual handling time ,	Insertion code	Insertion time (s)	Total operation time (s)	Theoretical minimum parts	Part name
1	1	80	4.1	00	1.5	5.6	1	Vessel
2	2	30	1.95	06	5.5	14.90	2	Handles
3	2	00	1.13	38	6.0	14.26	2	Screws
3	1			98	9.0	9.0	-	Turn assembly over
4	1	11	1.8	00	1.5	3.3	0	Elliptical ring
5	1	31	2.25	00	1.5	3.75	0	Metal disc
6	9	30	1.95	30	2.0	35.55	0	Ceramic inserts
7	1	05	1.84	41	7.5	9.34	1	Heating Coil
6	1	30	1.95	00	1.5	3.45	1	Wok support
7	1	30	1.95	00	1.5	3.45	1	Temperature changer
8	3	08	2.45	08	6.5	26.85	3	Metal wires
9	2	15	2.25	38	6.0	16.5	2	Nut
10	4			95	8.0	32.0	-	Soldering operation
11	1	33	2.51	00	1.5	4.01	1	Square strip
12	1	33	2.51	11	5.0	7.51	0	Locator strip
13	2	15	2.25	38	6.0	16.5	2	Nut
14	1	33	2.51	00	1.5	4.01	1	Top plate
15	2	15	2.25	38	6.0	16.5	0	Nut
16	1	10	1.5	30	2.0	3.5	1	Lid
17	1	10	1.5	30	2.0	3.5	1	Electric cord
					Totals	233.48	19	

Total number of parts is 33
Manual design efficiency EM = 3 x 19/233.48 = 24.41 %

Figure 13 Electric wok worksheet for the Boothroyd and Dewhurst DFA method.

Based on the Boothroyd & Dewhurst analysis several changes are possible. The locator strip (part 12) could be combined with the square plate (part 11) for location of the temperature changer. The top plate (part 14) can be snap fit into the wok (part 1). The coil (part 7) could be directly attached to the bottom surface of the vessel (part 1). Thus 14 parts has been eliminated from the product and assembly time is reduced. The revised manual design efficiency is EM = 3 x 19/125.87 = 45.28%

Conceptual DFA Analysis. Again, we apply the product architecture-based conceptual DFA method to the electric wok. A function structure for the electric wok is shown in Fig. 14. The module heuristics yield five modules: electricity, thermal energy, food, liquid and support.

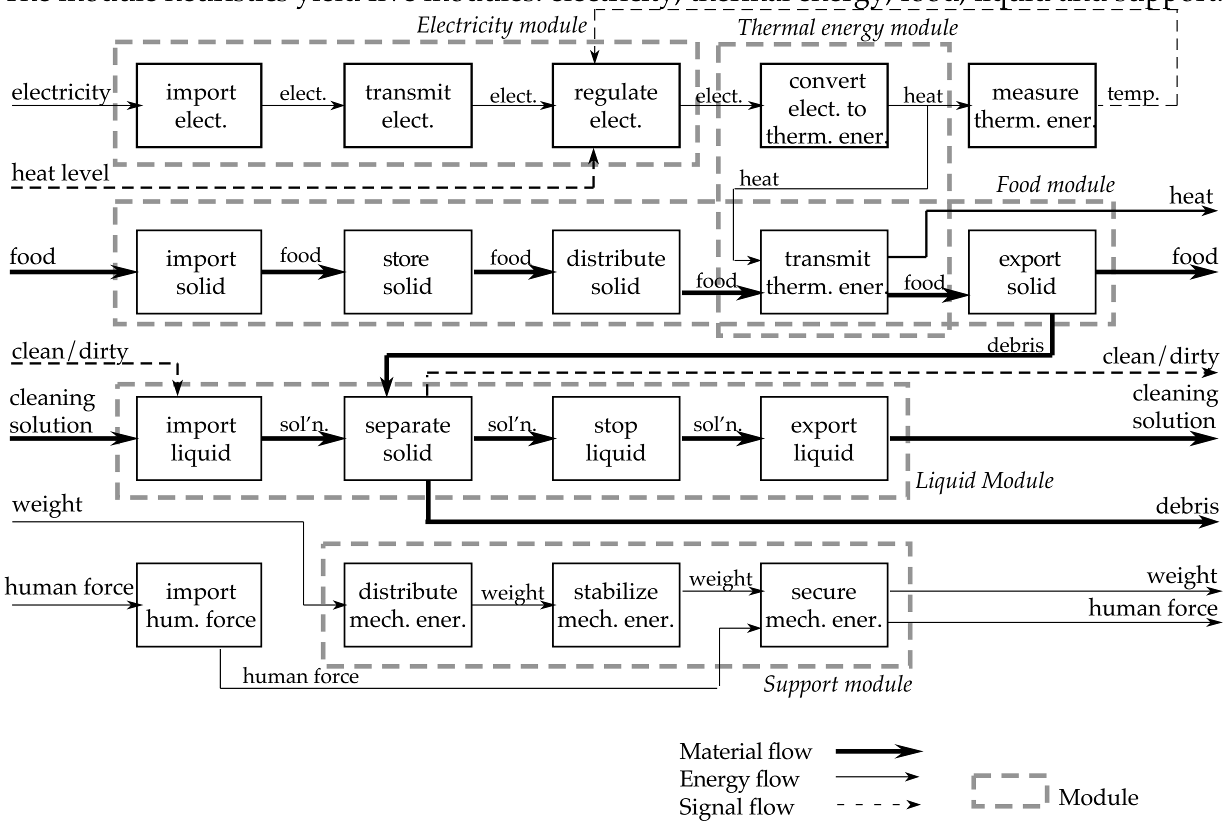
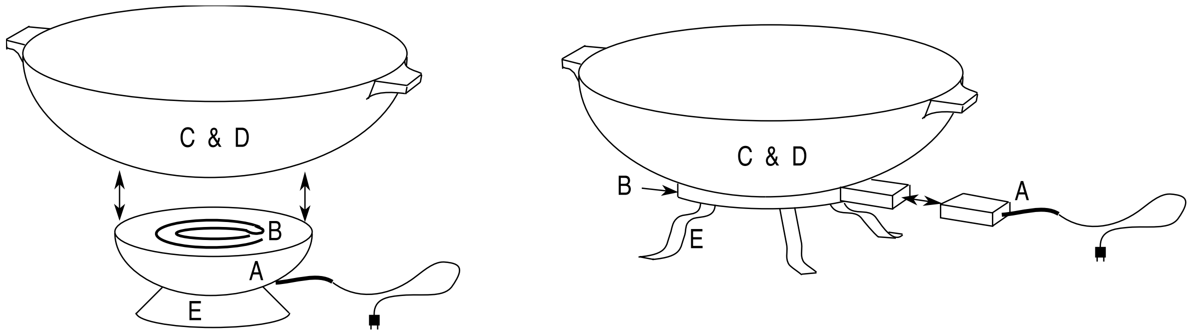


Figure 14 Function structure of the electric wok with identified modules.

The electricity module combines the functions of transmitting and regulating electricity. In the model under study these exist as two separate modules. A possible physical form of this module integrates a temperature sensing probe, temperature changer and electrical supply cord. The thermal energy module, consisting of a coil, supports and a metal shield in the present model, could be directly attached to the bottom of the vessel. The vessel identifies the food and liquid module, which is already a module. The support module can be a stand directly attached to the vessel. Two possible concept variants, developed from the product architecture-based method are shown in Fig. 15. Their module to part count is compared with the existing product in Fig. 16.



(a) (b)

Figure 15 Two wok concept variants with modules identified in the function structure: A – electricity module, B - thermal energy module, C – food module, D – liquid module, E - support module

Module	Existing Design Component descriptions	Part count	Time	Proposed Concept Component descriptions	Part count	Time
Electricity	Electric Cord	1	3.50	Electric supply and regulator	1	3.95
	Temperature changer	1	3.45	Cover	3	7.45
	Metal wires and soldering operation	3	58.85	Screws	4	14.26
	Nut	2	16.5			
	Square strip	1	4.01			
	Locator strip	1	7.51			
Thermal energy module	Heating coil	1	9.34	Heating coil at bottom of vessel	1	20.0
	Ceramic inserts	9	35.55			
	Top plate	1	4.01			
	Elliptical ring	1	3.30			
	Metal disc	1	3..75			
Food Module	Vessel	1	5.60	Vessel	1	5.60
	Handles	2	14.90	Handles	2	14.90
	Screws	2	14.26	Screws	2	14.26
	Lid	1	3.5			
Liquid module	Vessel	0		Vessel	0	
Support	Wok support	1	3.45	Wok support	3	3.45
				Screw	1	7.13
Other parts	Nut	4	33.0			
	Turn assembly over		9.0			
	Totals	33	233.48		13	91.0

Figure 16 Module to part count comparison of the existing and proposed design of the electric wok.

Figure 16 identifies components for the modules in the existing model and the proposed concept model. Any component solving more than one module is given ‘0’ as the part count when repeated. There are 33 parts in the existing design which are grouped according to the module they solve. The assembly time for these parts is 233.48 seconds. For the proposed concept model there are 13 parts with an assembly time of 91 seconds. Comparatively, the Boothroyd and Dewhurst analysis suggests a design with 19 parts and total assembly time of 134.87 seconds. Furthermore, it is based on modifying the existing product structure.

Summary. Both methods again produce a roughly equivalent reduction in part count. While the post design Boothroyd and Dewhurst DFA analysis leads to a redesign of the current product structure, the conceptual product architecture DFA analysis leads to more creative alternatives and a smaller part count.

Theoretical Minimum Number of Parts Summary

Examination of the electric wok reveals an assembly of 33 parts. The Boothroyd and Dewhurst analysis predicts a theoretical minimum number of parts as 19. The product architecture method gives a part count of 13. The advantage of the latter method is that the DFA analysis has been incorporated in the conceptual design stage itself.

The findings are similar in the case of the stapler. The Boothroyd and Dewhurst analysis give the theoretical minimum number of parts as 14. The product architecture method leads to an embodied minimum of 11 parts. Thus both methods lead to part count reduction with the difference being that the former is a post design DFA method and the latter being a conceptual DFA method.

In summary, the case studies reveal two main points: 1) significant part count reduction, comparable to existing post design DFA techniques, is achieved at the conceptual design level with the product architecture method and 2) the modules help the designer to identify and come up with creative concept forms.

The modules identified from the function structure enable a designer to explore various design solutions. As long as these solutions satisfy the functional requirement of the product and contains fewer parts for assembly, the solution is useful. The role of creativity in design cannot be underestimated.

3.2 Product Evolution – Shortening the Design Cycle

Structured design methodologies are a deliberate attempt to reduce product development cycles. In fact, if properly used, methodologies provide much more than incremental improvements in products, described as discontinuous jumps in a product's evolution s-curve (Asthana, 1995).

Here we look at the evolution of two products, a heavy duty stapler and an electric wok. In each case, the product evolves into versions with fewer parts. Additionally, the part count reduction bears striking resemblance to the conceptual forms that result from the product architecture-based DFA analysis.

Stapler Evolution

Three heavy-duty staplers are considered here, each from a different manufacturer. Stapler A is a mid 1950s design with a total part count of 34. Stapler B hit the market in 1994 and has 29 parts. Stapler C also entered the market in 1994, though with a radically different design and a part count of 21. Regardless of the form, the heavy-duty staplers considered here are all functionally equivalent. The stapler functional model is shown in Fig. 9. The three staplers are compared in Fig. 17.

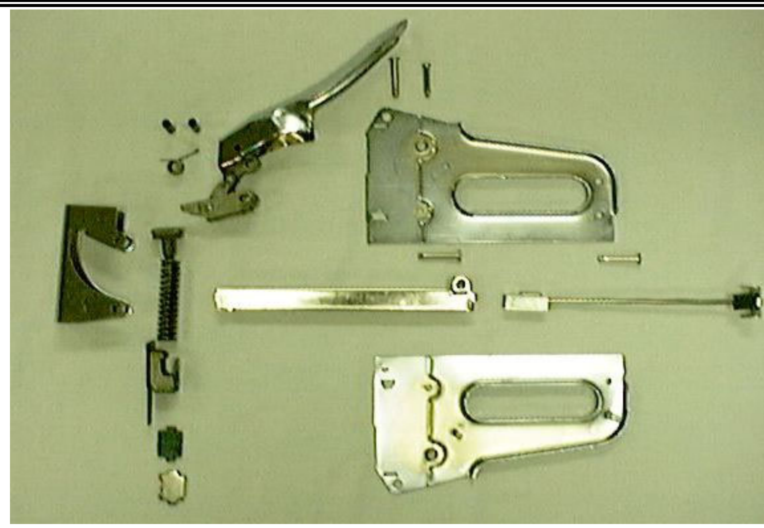
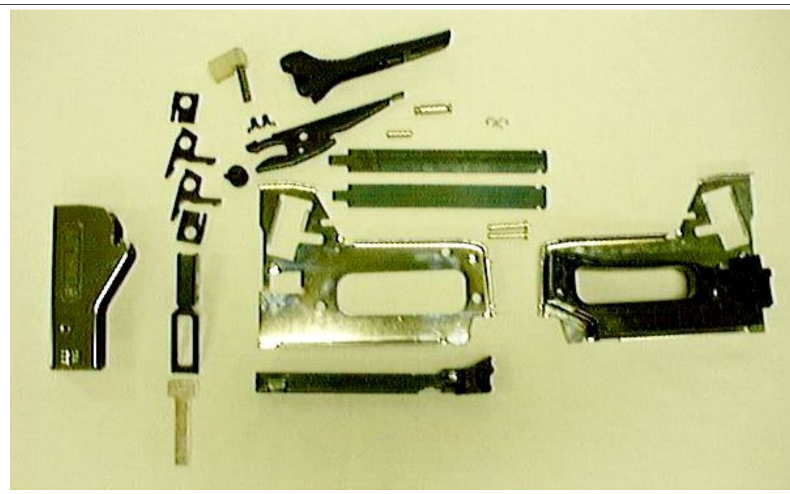
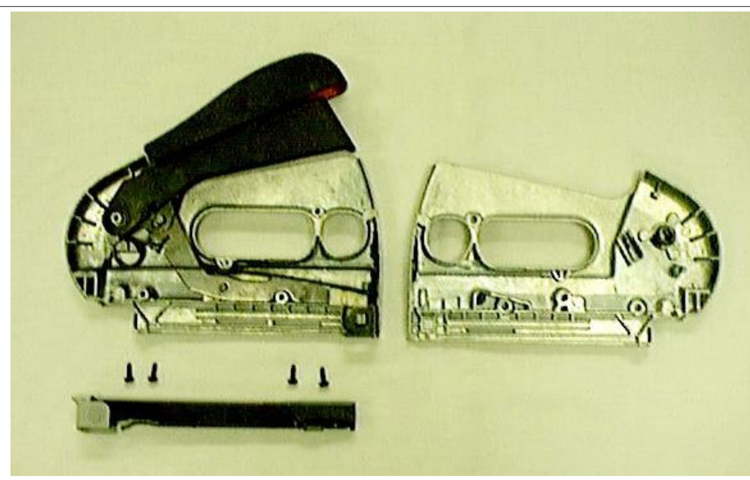
Stapler	Part count
 A	 34
 B	 29
 C	 21

Figure 17 A comparison of Staplers A, B and C with respect to part count.

Stapler A has a linkage to perform the upward motion of the hammer. This linkage is riveted to the handle and has many parts in its assembly. The hammer, in its upward motion, compresses a high stiffness spring to store energy and release it when actuated by the linkage. The human force required is the highest of the three staplers.

In Stapler B, a plastic pin moves in the slot of the handle assembly. This pin carries two lifters, which latch on to the two leaf springs. One of the leaf springs fits into the slot provided in the hammer. The handle in its upward motion deflects the two springs. When the lifters release the leaf springs they impart the required force to the hammer. In this design the linkage mechanism or the high stiffness spring of the Stapler A is not present.

In Stapler C, the lifters and the leaf spring of Stapler B are combined as one object to lift the hammer. The hammer in its upward motion deflects a bow shaped leaf spring to impart the necessary force for the hammer in its downward motion. This model has the fewest number of parts and requires the least force to operate. The casings are made through a casting process and features like storage space for staples are built into the casting itself. The two casings are attached with four screws, providing easy assembly and disassembly. This model satisfies the functional requirement of a heavy-duty stapler and is user friendly for the customer.

Of the three staplers, Stapler C's form most closely approximates the conceptual form developed by the conceptual DFA analysis in the previous section. The natural evolution of the stapler, covering 40 years, could have been achieved in a much shorter time following the product architecture-based DFA analysis.

Electric Wok Evolution

Similarly, two electric woks, each by a different manufacturer, are compared. Wok A (the wok of the previous section) has a part count of 33 parts and was introduced in the early 1990s. The second wok, Wok B, has a part count of 13 parts and entered the market in the late 1990s. Both woks functionality is described by the function structure of Fig. 14, though their form is different. The two are compared in Fig. 18.

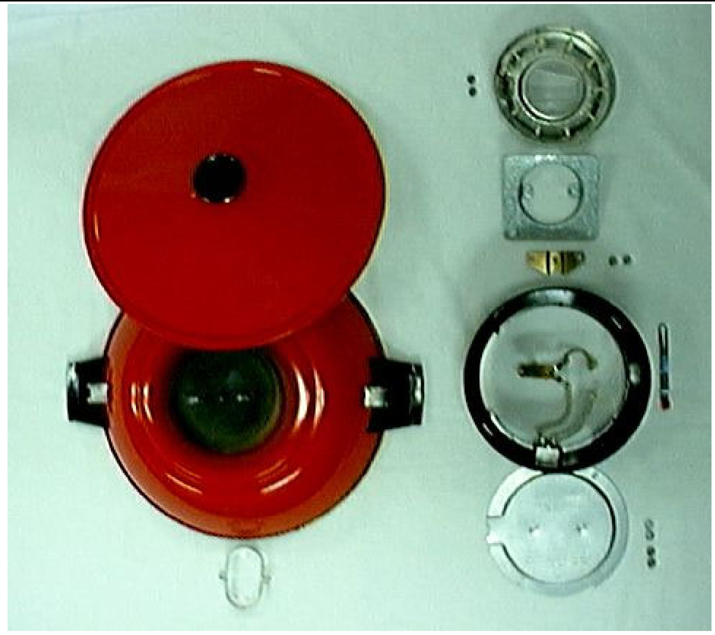
Wok	Part count
 A	 33
 B	 13

Figure 18 A comparison of Woks A and B with respect to part count.

Wok A has the heating coil provided in a metal disc. There will be heat loss to the atmosphere even though the coil is covered. The locator strip for the temperature changer and the square strip add to the parts in the assembly. The electricity supply and regulation exist as two different parts.

In the case of Wok B, the electricity supply and regulation exist as one part or one module. The heating coil is placed in a slot on the bottom surface of the vessel and covered completely. This model is similar to the form proposed by the product architecture-based method in the previous section.

Product Evolution Summary

The need for user friendly and high quality products for the customer has led to better designed products over the years. Industry realizes that a product loses market share if it does not satisfy its functional requirements and is not appealing to the customer. The need for high quality products at lesser cost has led the industry to cut costs of manufacturing and assembly and reduce the design cycle. In both the heavy duty stapler and the electric wok, the better designs evolved over a period of years into smaller part count products. The product architecture method captures this trend and allows it to be implemented at the conceptual level of design. By eliminating the need for multiple iterations, the design cycle is greatly reduced.

4 CONCLUSIONS AND FUTURE WORK

The two case studies presented above show considerable part count reduction both by the conceptual DFA method and Boothroyd and Dewhurst (B&D) DFA method. The B&D method leads to part count reduction after a redesign exercise on the existing product. With the help of manual handling chart and the manual insertion chart assembly times and theoretical minimum number of parts are calculated. Based on these numbers, redesigns can be developed and the resulting assembly times compared.

Developing product models based on the functional basis and applying the module heuristics, modular product architectures are developed and used for part count reduction at the conceptual design stage. This method also leads to creative solutions for product designs, and in the cases studies presented here, a greater reduction in part count then was achieved using the Boothroyd and Dewhurst methodology. This method is easily implemented and used by a design engineer for any product. Additionally, the product architecture method works with other quantitative methods to determine assembly time information. This method leads to savings in time and resources. The stapler and the electric wok were taken for this case study to show the product variety to which the conceptual DFA method can be applied.

The case studies presented above are from a set of consumer products under study to develop more creative DFA techniques. The resulting product architecture method is a predictive theory for product design; the method captures the way in which products evolve as the design is refined in an effort to reduce product cost while retaining customer required functionality. Thus, the product architecture based conceptual DFA technique can be used to accelerate the rate of product improvement, or perhaps achieve a fully mature design in a first product offering. Our study of existing and evolving products assemblies bear out the utility of the conceptual DFA method.

In the future, we will expand our study to investigate products of other scales (i.e. industrial use products, large home appliances and complex systems such as autos or aircraft). Also, cost measures will be added to the conceptual DFA method.

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