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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 developed and presented in this article 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 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.

Keywords: conceptual design methodology, product design, product development, innovation

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 implemen-

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tation 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 that may be applied in the conceptual design stage. The necessary input to this analysis is a 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, are used to guide the form solution in effort to produce a concept with the least parts possible.

The remainder of this paper 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

DFA addresses assembly quality largely through product structure simplification and reduction in the total numbers of parts in a product. Redford and Chal[1] 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] **Redford, A and Chal, J** *Design for Assembly—Principles and Practice* McGraw-Hill Inc, England (1994)

1.1.1 DFA systems using design principles and design rules

Design rules are empirical 'truths' verified by extensive design practice. Andreasen and Hein[2] and Redford and Chal[1] have framed rules, which help in this type of DFA method. Suh[3] 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),[4,5] the Boothroyd and Dewhurst method,[6] the Xerox Producibility Index[7,8] or assembly trees.[9] Extensions to such methods include the subtract–operate procedure and force flow analysis for piece count reduction in a product.[10] 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 3D 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.[11]

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2 **Andreasen, M and Hein, L** *Integrated Product Development* IFS (Publications) Springer-Verlag, New York (1985)

3 **Suh, N** *The Principles of Design* Oxford University Press, New York (1998)

4 **Ohashi, T, Miyakawa, S and Matsunaga, M** 'Automatic assembly line for VTR mechanisms' *Robotics* Vol 1 No 2 (1985) 89–96

5 **Suzuki, T, Ohashi, T, Asano, M and Miyakawa, S** 'Assembly reliability evaluation method (AREM)' in Proceedings of the IEEE International Symposium on Assembly and Task Planning (2001) pp 294–299

6 **Boothroyd, G** *Assembly Automation and Product Design* Marcel Dekker, New York (1992)

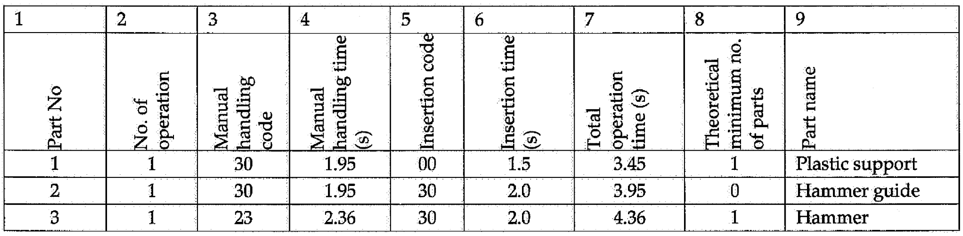
7 **Lewis, G** *Design for Assembly and Automation* Xerox Automation Institute, Webster, NY (1985)

8 **Waterbury, R** 'Applying design for assembly principles' *Assembly Engineering* (1986) 42–45.

9 **Ishii, K** 'Life-cycle engineering design' *Current Engineering and Design/Manufacturing Integration* Vol 81 (1995) 39–45(ASME Design Engineering Division (Publication))

10 **Lefever, D and Wood, K** 'Design for assembly techniques in reverse engineering and redesign' in Proceedings of the 1996 ASME Design Engineering and Technical Conference 96-DETC/DTM-1507, Irvine, CA (1996)

11 **Swift, K** 'Expert system aids design for assembly' *Assembly Automation* Vol 9 No 3 (1989) 132–136



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

1.2 Boothroyd and Dewhurst method

Boothroyd and Dewhurst[12] 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 Figure 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.

[12] **Boothroyd, G and Dewhurst, P** *Product Design for Assembly* McGraw-Hill Inc, New York (1989)

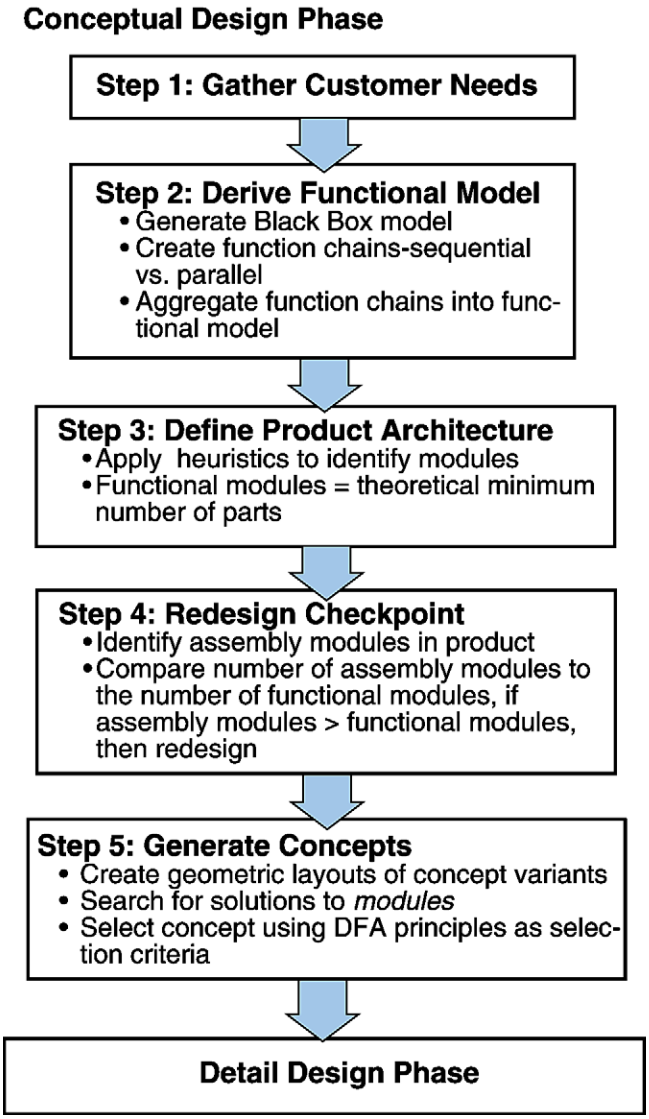


Figure 2 The product architecture-based approach to DFA

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).

Column (8) contains the theoretical minimum number of parts for the assembly that 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 using 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 is 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,[1] 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. Then, the focus of the conceptual design effort is to solve the overall product task module by module. If possible, the complete functionality of each module is solved by one part. 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 DFA principles have continuously been applied. Thus, DFA is realized with a substantial saving in time and overall effort.

Steps 1 and 4 focusing on customer need collection and concept synthesis of the conceptual design phase shown in Figure 2 are not discussed in detail here as there are many references which describe their application.[13–18] The steps specific to the DFA method presented here are discussed in detail in the next sections. These steps are the modified functional deri-

[13] **Pahl, G and Beitz, W** *Engineering Design: a Systematic Approach* Springer-Verlag, London, UK (1996)

[14] **Ullman, D** *The Mechanical Design Process*, 3rd ed. McGraw-Hill Inc, New York (2002)

[15] **Ulrich, K and Eppinger, S** *Product Design and Development* McGraw-Hill, New York, NY (1995)

[16] **Cutherell, D** ‘Product Architecture’ in **M Rosenau Jr.** (ed.) *The PDMA Handbook of New Product Development*, Wiley and Sons, (1996)(Chapter 16)

[17] **Otto, K** ‘Forming product design specifications’ in Proceedings of the 1996 ASME Design Theory and Methodology Conference, Irvine, CA (1996)

[18] **Stone, R, Wood, K and Crawford, R** ‘Using quantitative functional models to develop product architectures’ *Design Studies* Vol 21 No 3 (2000) 239–260

vation step (step 2) and the new step of defining product architecture (step 3).

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.[13–16, 19–23] 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. For the present work, function structures are expressed in terms of a common vocabulary known as the functional basis.[24–26] 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.

For the conceptual DFA technique presented here, we follow a five-step functional modeling derivation method previously developed by the authors that incorporates the functional basis and principles of function structure generation discussed above.[27–29] These steps, shown schematically in Figure 3(a), are: (1) identify flows that address customer needs; (2) generate a black box model; (3) create function chains for each input flow; (4) aggregate function chains into a functional model; and (5) verify the functional model with customer needs.

As an example, consider the functional model derivation of a portable food-cooking product shown in Figure 2(b). In this case, we will specify that the product be powered by electrical energy (i.e., a process choice on our part). Based on customer needs, the overall black box function of the product is formulated as 'cook food' and input and output flows are identified. Taking each input flow, a chain of functions operating on that flow is derived, for instance the flow of food is considered in Figure 2(b). After all of the function chains are derived, they are aggregated together to form the overall functional model of the product. Finally, customer needs are verified as being addressed by at least one function of the product.

19 **Hubka, V and Ernst Eder, W** *Theory of Technical Systems* Springer-Verlag, Berlin (1984)

20 **Schmidt, L and Cagan, J** 'Recursive annealing: a computational model for machine design' *Research in Engineering Design* Vol 7 No 2 (1995) 102–125

21 **Pimmler, T and Eppinger, S** 'Integration analysis of product decompositions' in Proceedings of the ASME Design Theory and Methodology Conference, DE, vol. 68 (1994)

22 **Shimomura, Y, Tanigawa, S, Takeda, H, Umeda, Y and Tomiyama, T** 'Functional evaluation based on function content' in Proceedings of the 1996 ASME Design Theory and Methodology Conference 96-DETC/DTM-1532, Irvine, CA (1996)

23 **Otto, K and Wood, K** *Product Design: Techniques in Reverse Engineering, Systematic Design, and New Product Development* Prentice-Hall, New York (2001)

24 **Hirtz, J, Stone, R, McAdams, D, Szykman, S and Wood, K** 'A functional basis for engineering design: reconciling and evolving previous efforts' *Research in Engineering Design* Vol 13 No 2 (2002) 65–82

25 **Stone, R B and Wood, K L** 'Development of a functional basis for design' *Journal of Mechanical Design* Vol 122 No 4 (2000) 359–370

26 **Little, A, Wood, K and McAdams, D** 'Functional analysis: a fundamental empirical study for reverse engineering, benchmarking and redesign' in Proceedings of the 1997 Design Engineering Technical Conferences 97-DETC/DTM-3879, Sacramento, CA (1997)

27 **Stone, R and Wood, K** 'Development of a functional basis for design' *Journal of Mechanical Design* Vol 122 No 4 (2000) 359–370

28 **Bryant, C, Kurfman, M, Stone, R and McAdams, D** 'Creating equation handbooks to model design performance parameters' in International Conference on Engineering Design, ICED 01 Glasgow, Scotland (2001)

29 **Kurfman, M, Stone, R, Van Wie, M, Wood, K and Otto, K** 'Theoretical underpinnings of functional modeling: preliminary experimental studies' in Proceedings of DETC2000 DETC2000/DTM-14563, Baltimore, MD (2000)

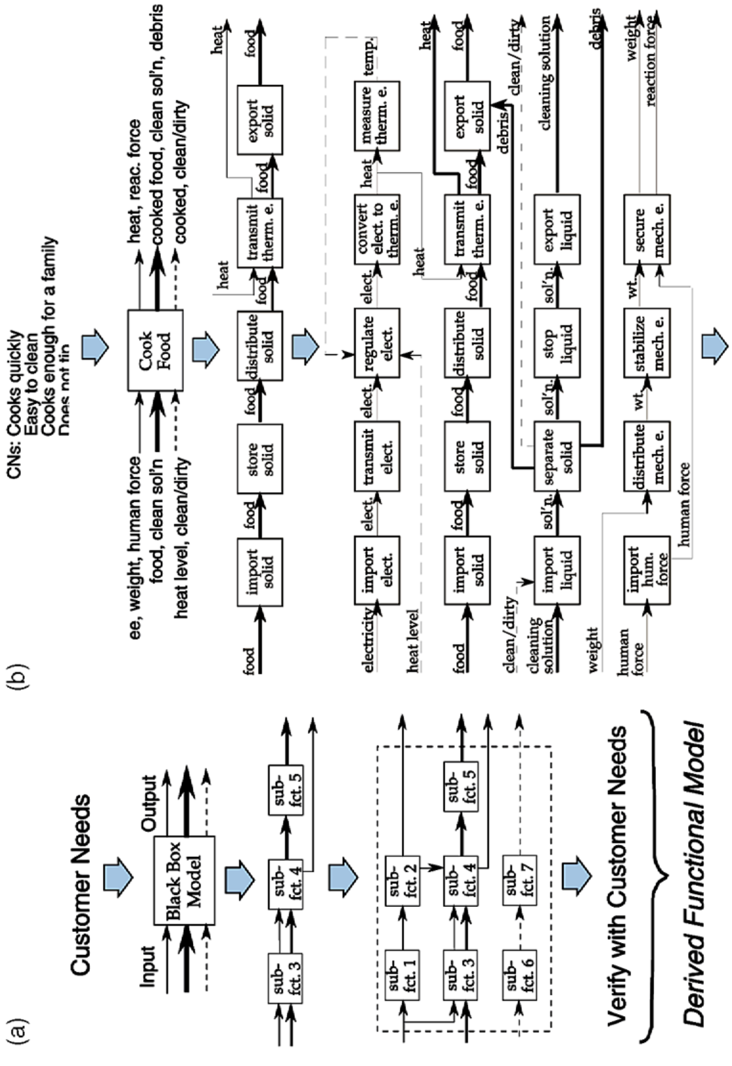


Figure 3 Steps of the functional model derivation method (a) and an example functional model derivation for a cooking product (b)

Table 1 Function classes and their basic categorizations

Class	Branch	Channel	Connect	Control magniture	Convert	Provision	Signal	Support
Secondary (or basic)	Separate	Import	Couple	Actuate	Convert	Store	Sense	Stabilize
	Distribute	Export Transfer Guide	Mix	Regulate Change Stop		Supply	Indicate Process	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 functional model expressed in the common language of the functional basis, sub-functions are clustered to define modular product architecture. We postulate that by generating solutions module by module during the conceptual design stage, a concept can be developed with a number of parts that is less than the theoretical number of parts produced by a post-conceptual DFA method. The modular product architecture method is modified from the product architecture definition method first proposed by Stone et al.[30, 31] and utilized in product architecture research.[32,33]

Stone et al.[34] develop a set of three heuristics to identify 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 heuristics are stated below and shown schematically in Figure 4–6.

> *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

[30] **Stone, R, Wood, K and Crawford, R** 'A heuristic method to identify modules from a functional description of a product' in Proceedings of DETC98 DETC98/DTM-5642, Atlanta, GA (1998)

[31] **Stone, R, Wood, K and Crawford, R** 'Product architecture development with quantitative functional models' in ASME Design Engineering Technical Conferences DETC99/DTM-8764, Las Vegas, NV (1999)

[32] **Gonzalez-Zugasti, J, Otto, K and Baker, J** 'A method for architecting product platforms' *Research in Engineering Design* Vol 12 No 2 (2000) 61–72

[33] **Yu, J, Gonzalez-Zugasti, J and Otto, K** 'Product architecture based upon customer demand' *ASME Journal of Mechanical Design* Vol 121 No 3 (1999) 329–335

[34] **Stone, R, Wood, K and Crawford, R** 'A heuristic method for identifying modules for product architectures' *Design Studies* Vol 21 No 1 (2000) 5–31

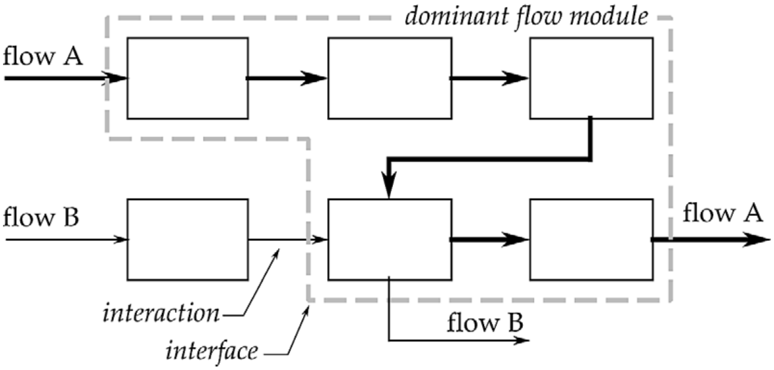


Figure 4 Dominant flow heuristic applied to a generic function structure

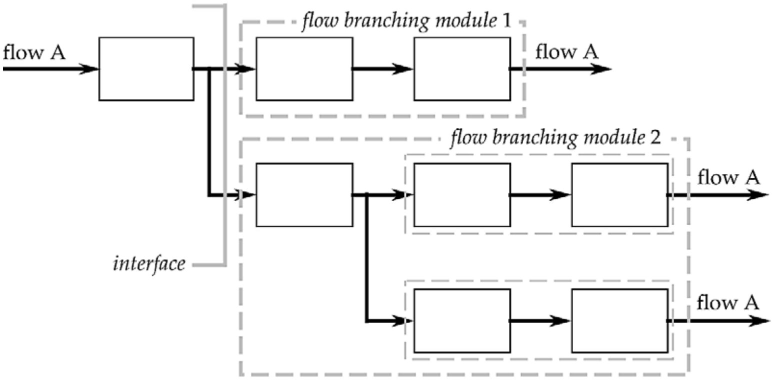


Figure 5 Flow branching heuristic applied to a generic function structure

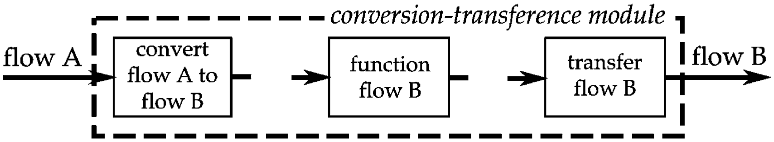


Figure 6 Conversion–transmission applied to a generic set of sub-functions

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.

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 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 reduced 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 reduced 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 the design methods: number of parts and assembly time

Here, we compare the number of parts that the conceptual (the product architecture-based method of Section 3) and post-design (Boothroyd and Dewhurst) DFA analyses produce during a redesign case study. Also, the manual assembly time required for the two resultant redesigns is calculated using the Boothroyed and Dewhurst method. Two products, a heavy-duty stapler and an electric wok, are considered in the following two case studies.

3.1.1 Case study 1: heavy-duty stapler

3.1.1.1 Post-design DFA analysis

The heavy-duty stapler considered here is shown in Figure 7. First, the Boothroyd and Dewhurst analysis for stapler is completed and shown in Figure 8.

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.

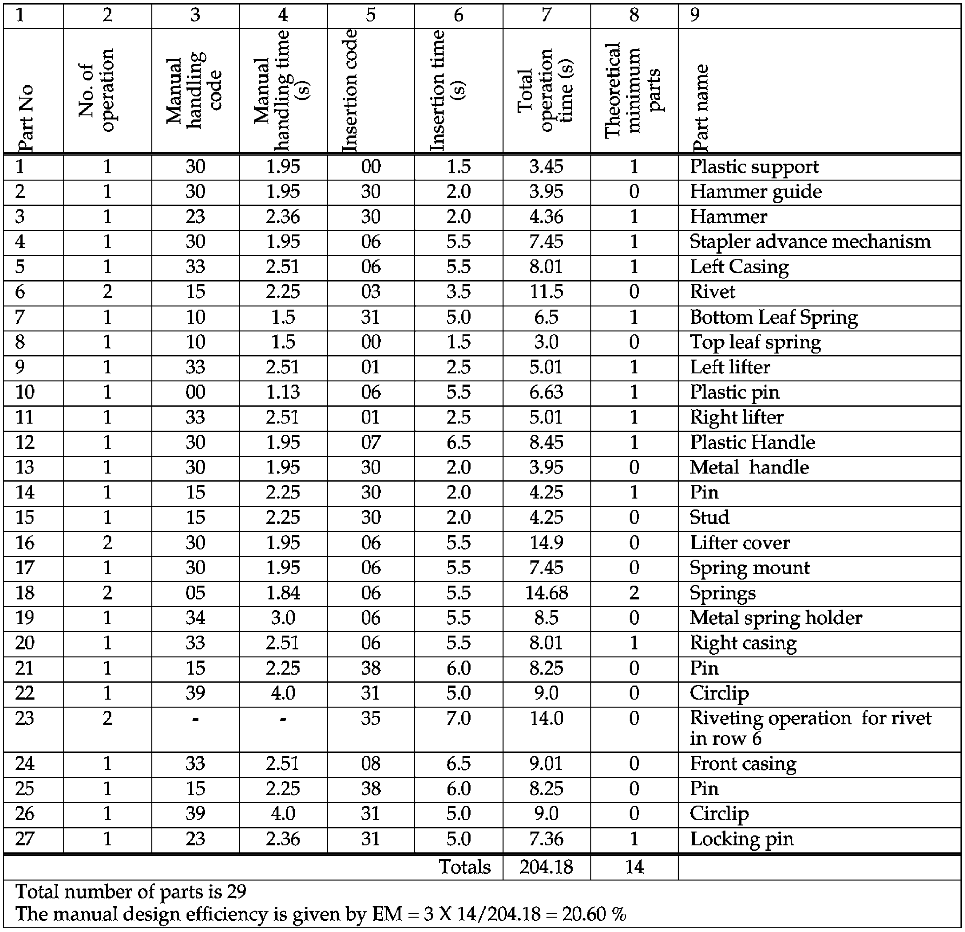
The analysis suggests several changes to the design, which can be

Figure 7 The heavy-duty stapler used in case study 1

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 and 20) could be attached by snap fits to the plastic support (part 1).
(c) The two leaf springs (parts 7 and 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 and 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 = $3 \times 14/89.17 = 47.1\%$, 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.



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 8 Boothroyd and Dewhurst assemply worksheet for a heavy-duty stapler

3.1.1.2 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 (1998)[35]. Note that an existing product is not necessary for our conceptual DFA analysis in general, but is necessary for our comparison with other post-design DFA techniques.

The stapler function structure is shown in Figure 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 *fully depressed* and *release* controls. The flows are operated on by the stapler and

[35] **Otto, K, Wood, N and Kristin, L** 'Product evolution: A reverse engineering and redesign methodology' *Research in Engineering Design-Theory Applications & Concurrent Engineering* Vol 10 No 4 (1998) 226–243

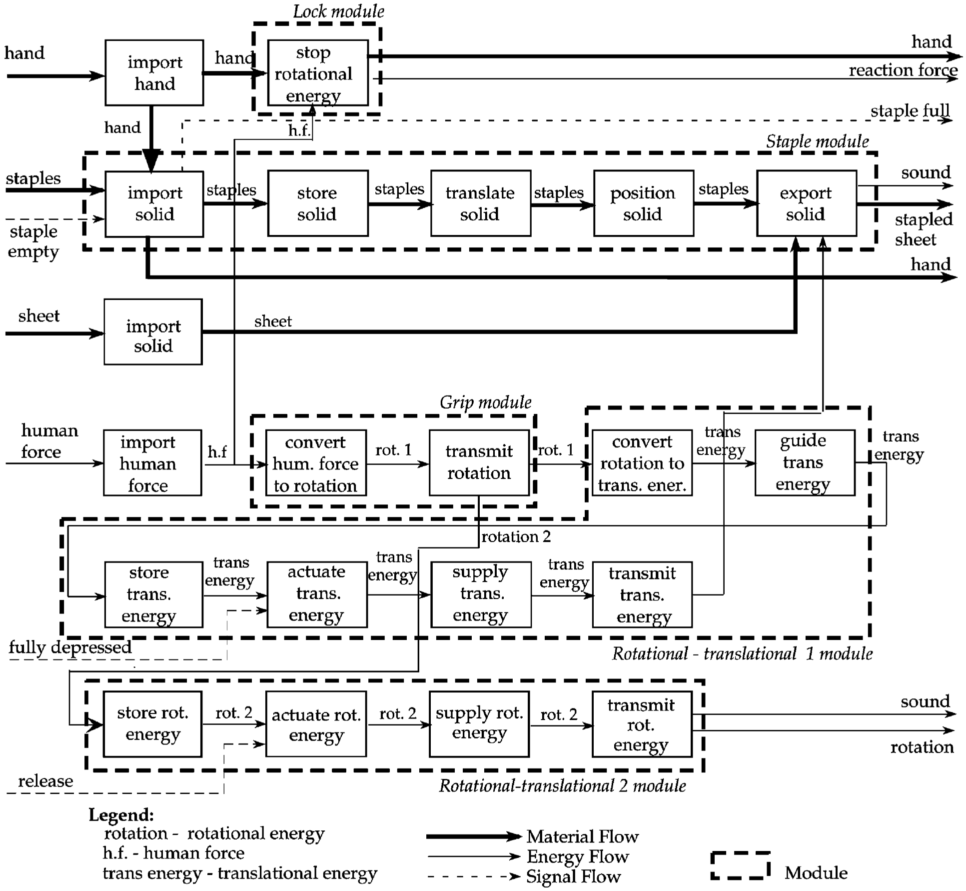


Figure 9 The function structure of a heavy-duty stapler with modules identified

expressed as sub-functions. Applying the module heuristics (step 3) identifies six modules: staple, rotation–translation 1, rotation–translation 2, grip, 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.

The six modules in Figure 9 are used to focus the conceptual design effort. The ideal goal is to solve each module with a single part. As with the Boothroyd and Dewhurst theoretical minimum, there are physical possibilities that preclude this six component ideal from being achieved. Nevertheless, using the one module—one part ideal as a goal, a concept is

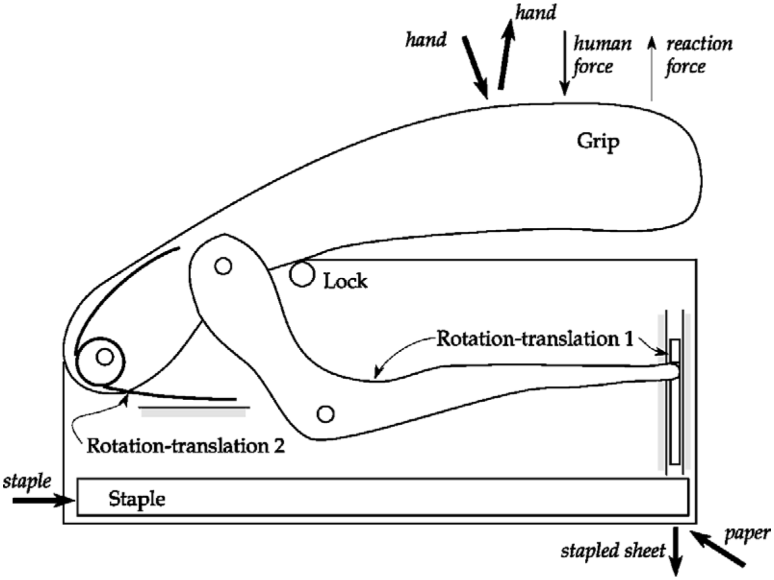
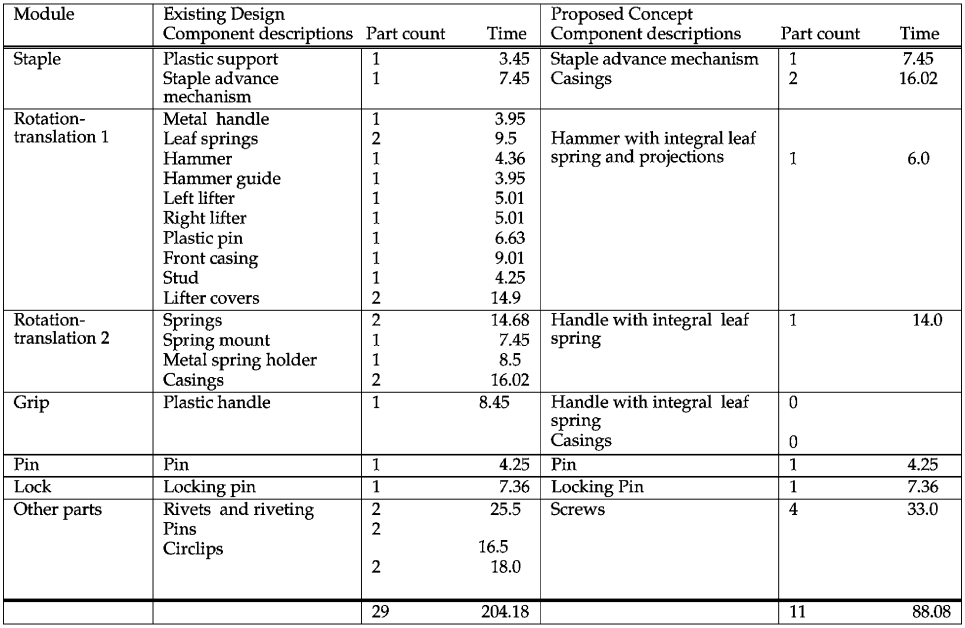


Figure 10 Form given to the modules proposed by conceptual DFA method

developed. The proposed conceptual design of the stapler is shown in Figure 10. The module to part count comparison for the existing stapler and the conceptual stapler (based on the six modules) is shown in Figure 11.

Figure 11 identifies components for the modules in the existing model and



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 Modulus to part count comparison of the existing and proposed design of the stapler

the proposed concept model. There are 29 parts in the existing design, which can be assigned to the modules identified from Figure 9. The assembly time is 204.18 s. For the proposed concept developed by the product architecture-based DFA method, there are 11 parts and assembly time is 88.08 s. The assembly time is determined using the Boothroyd and Dewhurst manual assembly time estimate.

3.1.1.3 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 yields a stapler design with only 11 parts. The assembly time of the two proposed designs is essentially the same. The two methods 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 DFA principles during concept generation.

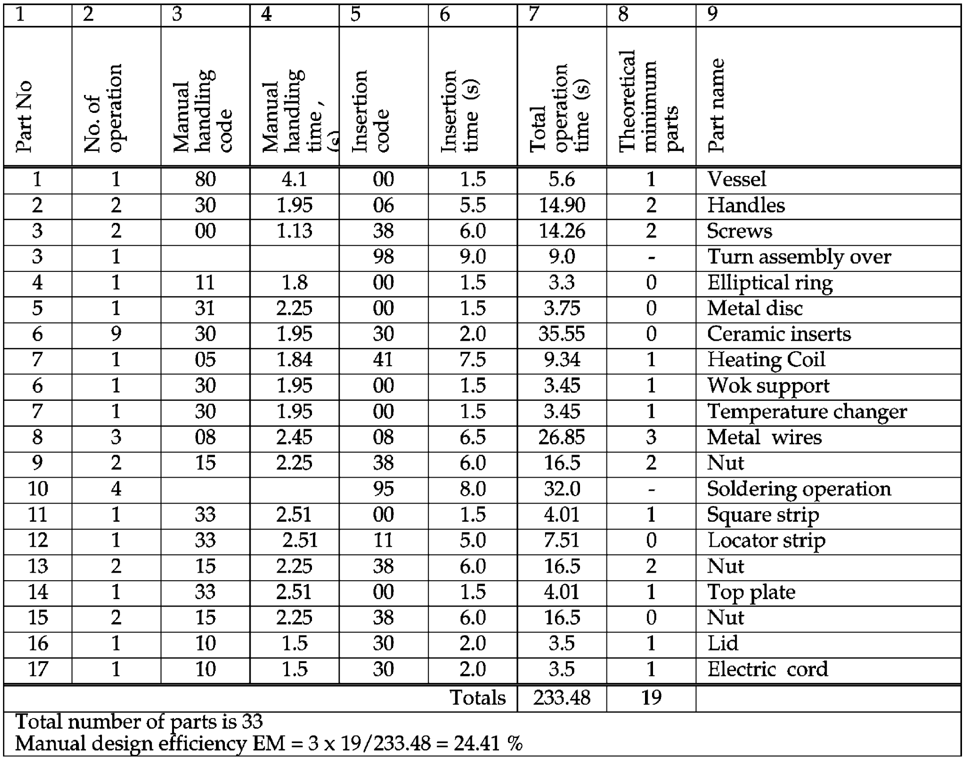
3.1.2 Case study 2: electric wok

3.1.2.1 Post-design DFA analysis

The electric wok considered here is shown in Figure 12. First, the Boothroyd and Dewhurst analysis for the wok is completed and shown in Figure 13.

Based on the Boothroyd and 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)

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 , (s)	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 work worksheet for the Boothroyd and Dewhurst DFA method

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 = 3×19/125.87 = 45.28%.

3.1.2.2 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 Figure 14. The module heuristics yield five modules: electricity, thermal energy, food, liquid, and support.

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.

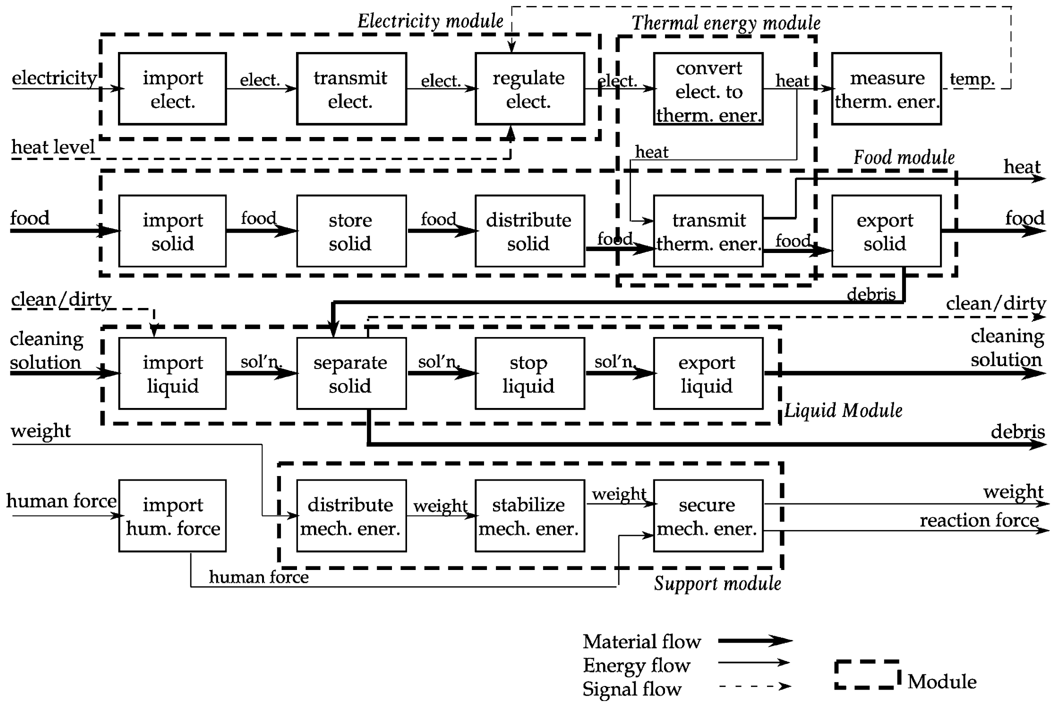


Figure 14 Function structure of the electric wok with identified modules

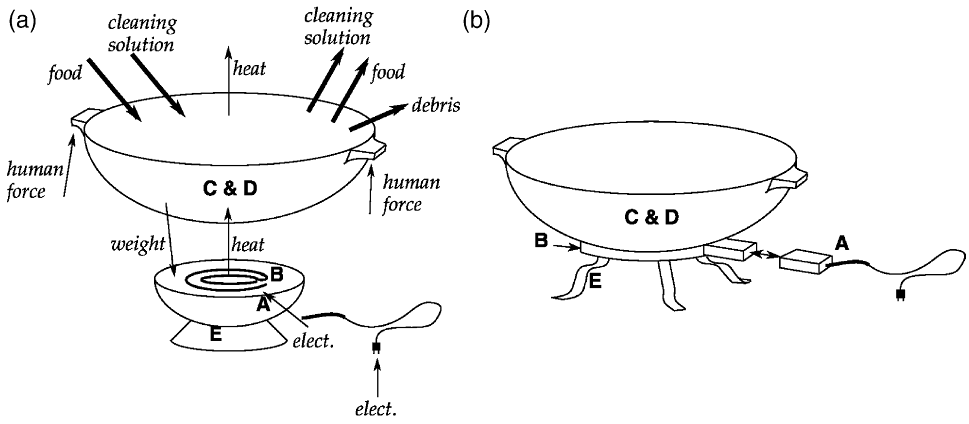


Figure 15 Two wok concept variants with modules identified in the function structure: A—electricity module, B—thermal energy module, C—food module, D—liquid module, E—support module

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 Figure 15. Their module to part count is compared with the existing product in Figure 16.

Figure 16 identifies components for the modules in the existing model and

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

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 that are grouped according to the module they solve. The assembly time for these parts is 233.48 s. For the proposed concept model, there are 13 parts with an assembly time of 91 s. Comparatively, the Boothroyd and Dewhurst analysis suggests a design with 19 parts and total assembly time of 134.87 s. Furthermore, it is based on modifying the existing product structure. All of these assembly times are determined using the Boothroyd and Dewhurst manual assembly time estimate.

3.1.2.3 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.

3.1.3 Part count 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 produces an embodied 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 gives 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.

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.[36]

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.

3.2.1 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 Figure 9. The three staplers are compared in Figure 17.

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.

[36] **Asthana, P** 'Jumping the technology S-curve' *IEEE Spectrum* June (1995) 49–54

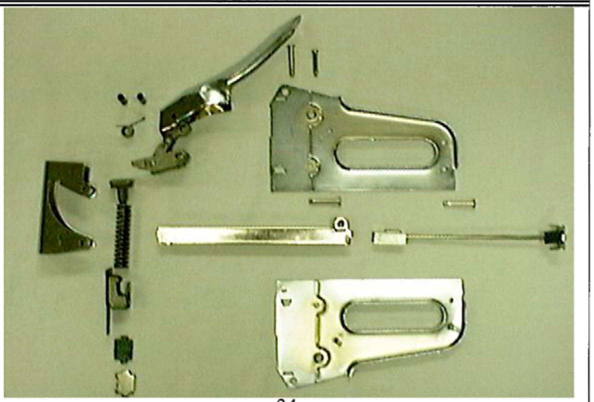
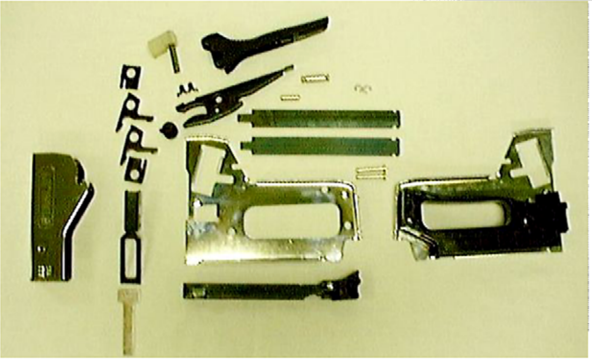
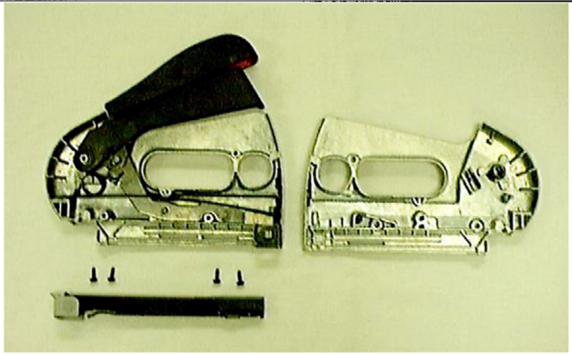
Stapler	Part count
 A	 34
 B	 29
 C	 21

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

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, is reproduced using the product architecture-based DFA analysis presented here. Thus, if appropriate materials are selected and manufacturing technologies are available such as casting as used in Stapler C, the long evolution of the stapler design could have been shortened dramatically through usage of the DFA method presented here.

3.2.2 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 Figure 14, though their form is different. The two are compared in Figure 18.

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.

3.2.3 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

Wok	Part count
 A	 33
 B	 13

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

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 bears 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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