DESIGN FOR ASSEMBLY TECHNIQUES IN REVERSE ENGINEERING AND REDESIGN

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ABSTRACT

Design for Assembly (DFA) is the process by which a product is designed to be easily assembled. Such design simplifications are accomplished through reducing the number of operations required to assemble the product, improving the handling of each component, and/or modifying the required operations (insertion, joining, etc.). There exist several techniques for assessing the assemblability of a design through an analysis of these three aspects. However, there also exists a clearly defined need for evolving such techniques to indicate how a product should be redesigned with respect to customer needs and associated functionality. This paper presents three such straightforward evolutions, aimed at reducing the number of components in an assembly during redesign. The first technique is a component elimination procedure, the second technique is a component combination analysis, and the third technique establishes a logical approach for revealing more abstract component elimination or combination opportunities. These three DFA techniques are integrated within a reverse engineering and redesign methodology. They are then applied to a industrial design application, i.e., redesign of an auxiliary automobile visor. Results demonstrate definitive part count reduction, while maintaining and improving design functionality.

1 INTRODUCTION: REVERSE ENGINEERING, REDESIGN, AND DESIGN FOR ASSEMBLY

Reverse engineering is a redesign methodology. This means that it is a design process that is applied to an existing product, or at least to a prototype or detailed concept. It is normally a process that uses a variety of techniques in the form of models, charts, diagrams, guidelines, and normative theories to dissect and fully understand a product. Stated consisely, reverse engineering "...initiates the redesign process, wherein a product is observed, disassembled, analyzed, and documented in terms of its functionality, form, physical principles, manufacturability, and assemblability. The intent of this process step is to fully understand and represent the current instantiation of a product (Otto and Wood, 1996). "

Although reverse engineering is most widely used for redesign purposes, it can be used for other reasons as well. There exists at least five possible motivations behind reverse engineering a product: (1) benchmarking, (2) critical study and evaluation of a competitor's product, (3) quality improvements, (4) cost reduction, and (5) basic product/technology knowledge. Within this context, there can exist sub-design processes and methods that focus on a specific aspect of the design. Highly popular examples of these are Design for Manufacturing (DFM) and Design for Assembly (DFA).

Design for Assembly

Design for Manufacturability and Design for Assembly can be considered sub-design processes. They are techniques that focus on specific issues (manufacturability and assemblability) within a design. In recent years, design for manufacturability (DFM) have drawn a lot of attention. Companies have invested a great deal of effort and resources into new manufacturing techniques like gas-assisted injection molding, powder metallurgy, and laser beam machining (Kalpakijia, 1992). DFM software packages such as Computer-Aided Process Planning (CAPP) (Kalpakijia, 1992) have provided engineers with tools during the design stages (Ullman, 1992; Dixon and Poli, 1995; Ulrich and Eppinger, 1994; Ettlie and Bridges, 1990).

Assembly techniques have also received some focus. However, even though assembly typically accounts for between 40 and 60% of the overall production time (Andreasen, 1983), it has not received the same type of attention as manufacturing. Most of the progress in the assembly domain has come through studies of time and motion, division of work, and through the use of robotics and automation.

Overall, only partial emphasis has been placed on assembly during the design phase. M. Andreasen, S. Kahler, and T. Lund blame this limited consideration for assembly during design on lack of time or deficient time planning, lack of realization as to the importance of assembly, lack of knowledge of design oriented assembly, the habit of saying "they usually work it out in production.", and/or organizational problems which restrict a fruitful co-operation between employees from various functional areas (Andreasen, 1983).

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It is the presumption of this research that these problems are not the source, but rather the need for further techniques in the area of DFA. This is not to say that DFA methods do not exist. Geoffrey Boothroyd and colleagues published their Product Design for Assembly manual in 1982 (Boothroyd, Poli, and Murck, 1982; Boothroyd and Dewhurst, 1989, 1994; Ulrich and Eppinger, 1994). This manual is regarded as the father or pioneer of DFA techniques. It is composed of a formalized step-by-step approach which they summarize as first, a selection of the assembly method - manual, high-speed automatic, or robot assembly, then an analysis of the design using a Design for Assembly Worksheet. The worksheet (or spreadsheet) takes into account factors such as handling time, geometries, insertion time, and theoretical minimum number of parts to give an evaluation of the design which they label a product's "design efficiency." Besides Boothroyd and Dewhurst, many other DFA techniques have contributed to the field and this research. They include (Poli, Graves, and Groppetti, 1986; Ishii, et al., 1995; Defazio and Whitney, 1987; Pine, et al., 1993; Lee and Yi, 1994; Kim and Bekey, 1993)

Current DFA methods do a fine job of determining the assemblability of a product. However, it would be desirable to have a DFA method which would point directly at the solutions needed to create a design that is more easily assembled. This situation is where the current DFA techniques have some limitations. They expose the areas which negatively effect how easily a product is assembled, but they do not provide an approach for solving these issues. It is extremely important to know why a particular design can be improved for ease of assembly, but linking this knowledge is a larger, more abstract problem.

Niche: Piece Count Reduction in Redesign

This paper focuses on the aspect of DFA which considers piece count reduction. Piece count reduction means decreasing the number of parts that compose a product through either (1) elimination or (2) combination with other parts.

Piece count reduction in many cases is the most effective means of improving assembly. Fewer parts means fewer operations, less handling, and quicker assembly (besides special cases identified by Hinckley (1993)). Piece reduction also has broader implication. For example, Douglas Commercial Aircraft Co. ran simulations to determine what drives the cost of their airline construction. They discovered that in addition to the costs of assembly, the costs of fabrication, quality assurance, and even overhead-inventory levels, tracking, and purchasing all depend on piece count (Ashley, 1995). Therefore, techniques that aid in redesigning a product for piece count reduction are needed. This paper presents techniques that help to accomplish this task. The following is a list of the supporting objectives covered in the paper: (1) extend reverse engineering and DFA (piece count reduction) techniques; (2) develop a simple methodology to integrate DFA (piece count reduction) techniques into an existing reverse engineering methodology; and (3) apply the methodology to industrial applications.

A Reverse Engineering and Redesign Methodology

The basis for our study for redesign is the reverse engineering and redesign methodology, shown graphically in Figure 1 (Otto and Wood, 1996; Ingle, 1994). This methodology represents a ten-step process. It is a compilation of contemporary and extended engineering design techniques, logically arranged in a systematic approach

The first six steps of the process aim at predicting and hypothesizing a product’s architecture, gathering and organizing customer needs, and subsequently developing a complete understanding of the product through disassembly, functional analysis, compatibility studies, and physical modeling. The techniques used in these steps provide a means of not only understanding the physical product which is being analyzed, but also a mode for understanding the design rationale that motivated the existing design. This rationale leads to a comprehension of the "Whys" that motivated the "Hows" of a product. Steps 1-6 provide the supporting structure for steps 7-10 which deal with the redesign of the product at a parametric, adaptive, and/or original level.

2 TECHNIQUE EXTENSIONS: REDESIGN FOR PIECE COUNT REDUCTION

The intent of this section is to present three techniques aimed at linking the evaluation of the assemblability of a product to the redesign of the product. There are many different types of redesign that could lead to better assemblability. For instance, parametric redesign can be used to adjust feature dimensions so parts can be handled or inserted more easily. The techniques presented below, however, focus on redesign for piece count reduction at a higher level of abstraction. This type of design is usually adaptive design and sometimes requires original design. Parametric redesign is less likely to be used, as reduction of piece count usually requires a combination of parts. However, if pieces can be simply eliminated from an assembly, parametric redesign may be required to compensate for variations caused through this elimination. An example of this is shown in the case study in a subsequent section. The three techniques developed for aiding in redesign for piece count reduction are:

- Subtract and Operate Procedure
- Force Flow Diagrams
- Boothroyd & Dewhurst Extension

Each of these are explained through text and examples. For the Subtract and Operate Procedure, a simple mechanical example is used. For the Force Flow Diagrams and the Boothroyd & Dewhurst Extension, a current stapler product in the market is studied. Additional examples may be found in (Lefever, 1995). Also included is a discussion of how and where the techniques are integrated into the reverse engineering and redesign methodology, captured in Figure 1.

Subtract and Operate Procedure

Often, a product is over-designed. An over-designed product is one that uses multiple solutions to solve subfunctions which could more efficiently be solved using fewer or a single solution. If this situation occurs, there is an opportunity for elimination of components producing the redundancy. Identifying any redundant components can be a difficult undertaking. The Subtract and Operate Procedure (SOP) is a five step procedure aimed at exposing redundant components in an assembly through the identification of the true functionality of each component:

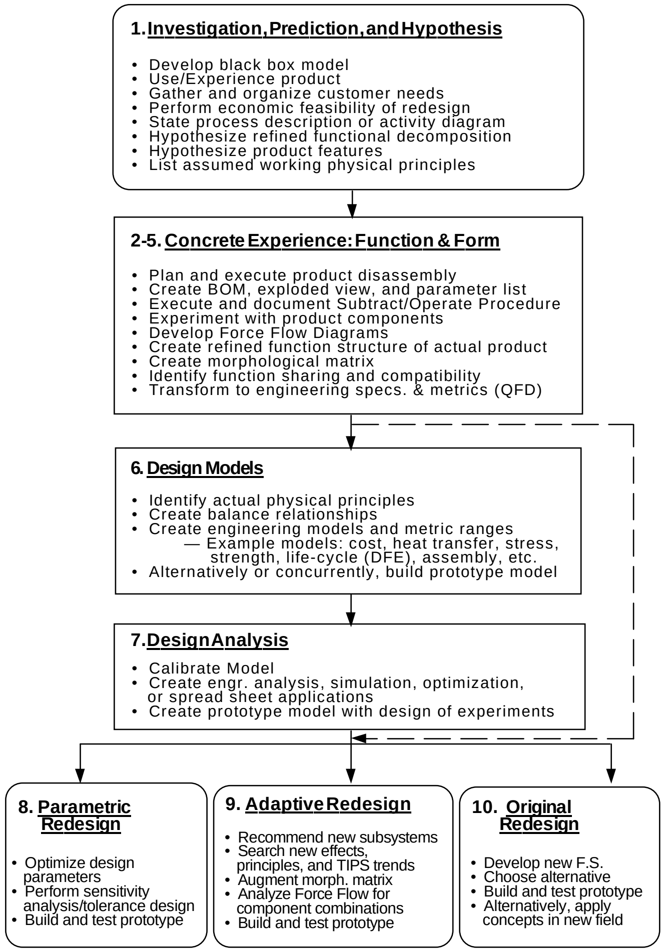

Figure 1. A Reverse Engineering and Redesign Methodology.

Step 1: Disassemble (subtract) one component of the assembly. Removal of components may occur in any order. However, it may be necessary to remove one or several components in order to remove the desired component. These prerequisite components should be reassembled if possible. If they cannot be reassembled, measures can be used to replicate the function(s) of the missing component(s). These measures are discussed later in this section.

Step 2: Operate the system through its **full** range. This step should test the product through the range of customer and associated engineering requirements requirement (structural, ergonomic, kinematic, etc.). After removing a component, the product should be thoroughly tested to verify the effect of removal.

Step 3: Analyze the effect. This step is most commonly completed through a visual analysis. However, it may be necessary to use a testing device if the effect of removal is not obvious.

Step 4: Deduce the subfunction(s) of the missing component. From step 3, the subfunction of the missing component may be deduced. A change in any DOF during operation should be a major focus. This issue is critical in determining component redundancies, as discussed in this section.

Step 5: Replace the component and repeat the procedure n times, where n is the number of pieces in the assembly. Step 5 is the reassembly of the removed component. Repeating the process n times allows for the analysis of each component in the assembly. In certain cases, it may be necessary to analyze a product according to subassemblies and components. This is also touched on later in this section.

An example is given using a simple rotational constraint mechanism. This mechanism is a simple example used to clearly exhibit the SOP. The case study discussed later in this paper is a more complex, real world example. Following the example is a discussion of where the SOP should be integrated into the redesign methodology.

SOP Example

Figure 2 shows an exploded view of a mechanism used to oscillate an arm through a designated range. The arm is connected to a rotary shaft which oscillates. The shaft oscillates, but the range of rotation is constrained by the pins and the top plate slots.

When applying the SOP five step procedure, it is useful to construct a matrix. Part number, part description, part function(s), and the observed effect(s) of operating the assembly without the part are items that should be documented (in addition to the relationships with the customer needs). For the mechanism shown in Figure 2, the worksheet is completed, as documented in Table 1. The SOP exposes five parts that are potential redundant components, denoted as "No effect" parts.

Examining Figure 2, only one of the rotary pins is required to constrain the shaft's range of rotation. For the arm pins, only one of the vertical pins (left or right) is required to constrain all degrees of freedom of the arm. (This assumes that large loads are not applied to the arm and that the arm is square, rigid, and tightly toleranced with the shaft). Removing the horizontal pin has no effect as the arm will not slip against the shaft because of the fixed vertical pins. A guideline in using the SOP is, if a component has "No effect", leave it off and continue on to the next component. Hence, with the horizontal pin still removed, one of the vertical pins is removed.

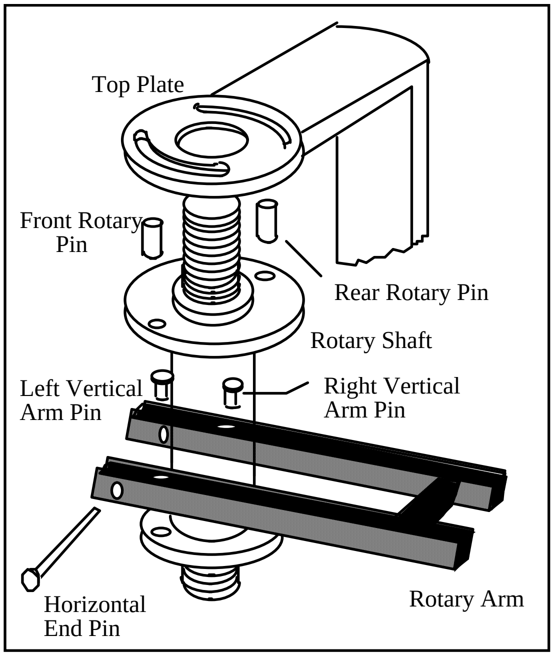

Figure 2: SOP Example Device.

When the system is operated, there is still "No effect" as the geometry of the arm and shaft along with the one fixed pin restrict any motion.

For the purpose of this paper, classifying components as changing or not changing the DOF of a design when they are removed is the critical determination. This leads to the following proposition: *Removed components causing no change in the DOF of the design are candidates for removal. Those components that cause no change in the DOF as well as no other effects are termed Type 1 redundant components and can be eliminated from the design. Those components that cause no change in the DOF, but have other effects due to their removal, may be removed if another component can be parametrically redesigned to compensate for these effects. These are Type 2 redundant components.*

Table 1: SOP Example Device Worksheet.

Part No.	Part description	Effect from Removal (Functions and Customer Needs)
1	Top Plate	360 degree rotary freedom
2	Rotary Shaft	No torque transfer
3	Front Rotary Pin	**No effect**
4	Rear Rotary Pin	**No effect**
5	Rotary Arm	No torque transfer
6	Horizontal End Pin	**No effect**
7	Right Vertical Arm Pin	**No effect**
8	Left Vertical Arm Pin	**No effect**

Figure 2 is an example of Type 1 redundancies. An example of a Type 2 redundancy is a drawer with a handle. If the handle is removed, a ledge can be used to pull out the drawer, but the effect is that there is an "Increase in pinch/grip effort." The drawer ledge geometry could parametrically be redesigned to accommodate a hand and act as a handle. In a manner of speaking, the handle is a redundant component.

The SOP can have limitations depending on the product being disassembled. Many times, the disassembly of a component requires the disassembly of other components. The simple example of a screw joining one block to a fixed block illustrates that to remove one block, the screw will have to be removed as well. Components such as the screw in this case, can be considered functionally dependent components. This means that the screw's function is dependent on the removed block. Once the block is removed, the function of the screw becomes obsolete and the operation of the system will not be affected by its absence. In the case where the screw not only holds together one block, but also a second block to the fixed block, the screw would be re-inserted before operation as it is functionally dependent on both blocks.

There are situations in which operation of the product is difficult when a component is removed. For these cases, it is useful to think of a product in a hierarchical manner: product, assemblies, subassemblies, etc. Decomposing the product into subassemblies and applying the SOP to each subassembly can eliminate the challenging or impossible task of operating the entire system. Components confined to the subassembly can be evaluated without regard to the rest of the assembly. Subassembly components interfacing with components outside of the subassembly should be evaluated as they are integrated. In some cases, this evaluation may take some creativity. External actuating or mounting tools can be used to resolve operating challenges.

Integration: SOP and Reverse Engineering

Figure 1 shows how the SOP technique integrates into A Reverse Engineering Design Methodology. Step 2 of the methodology is the disassembly of the product. At this stage, the part number, part description, and function for each component is documented. The SOP worksheet could essentially be an extension of the Bill of Materials. The "Effect" column would need to be added.

In addition, the morphological analysis, in Step 4 of the methodology, can act as a redundancy check. Recall, in a morphological analysis (Otto and Wood, 1996; Pahl and Beitz, 1989), the solution principle(s) (columns) are given for each subfunction (rows). For subfunctions solved by multiple solution principles, the different solution principles will appear in multiple columns. For a subfunction that is solved multiply by the same solution principle, the redundant solution principles will appear in as many columns as it is used in the design. This process is how redundancy discovered in the SOP will appear in the morphological matrix.

For an over constrained design, in which "No effect" appears for a Type 1 component in the SOP worksheet, the subfunction embodied by the component will have redundant solution principles. Furthermore, solution principles will not appear anywhere else in the morphological matrix as function sharers, unless they are redundant for given subfunctions as well. If a component is deemed as a Type 2 redundant component, its solution principle will be a member of a set of solution principles for a subfunction. Of the other solutions principles in the row, one or more of their corresponding components can be parametrically altered to compensate for the elimination of the Type 2 redundant component. Therefore, the analysis of Type 2 redundancies should begin in step 6: Mathematically model product. The components involved in the parametric redesign should be modeled. In steps 7-8, the model should be solved, and the parametric redesign should be instituted.

Force (Energy) Flow Diagrams

While the SOP is a simple, common-sense method for exposing components for elimination, Force Flow Diagrams focus on the component combination. This concept is accomplished through modeling of the design, then an analysis of the model.

Force Flow Diagrams are diagrams which represent the transfer of force through a product's components. The components are symbolized using circles (or squares), and the forces are drawn as arrows connecting the components in which the force transfer takes place, while maintaining the general topological arrangement of the components. Consider the example of the three-piece paper clip shown in the Figure 3(a).

In this case, the hand transfers the force to each of the lever arms. These arms in turn transfer the force to the clip, as represented with the Force Flow diagram in Figure 3(b).

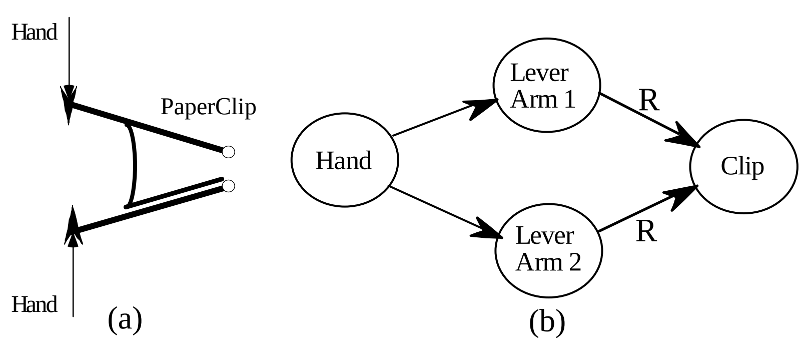

Figure 3. Paper Clip Example.

The motivation behind constructing a Force Flow Diagram of a product is to map the force flow through a product so that the diagram can be analyzed to help expose opportunities for component/piece combination. The first step in analyzing a Force Flow Diagram is to place an "R" on the flows that have relative motion between two components. Once this step is completed, the diagram can be decomposed into groups separated by "R's." Having performed this separation, the following proposition can be made: *the components of the "R" groups can be easily combined if not prohibited by material or assembly/disassembly issues. Combination between a member of one group and a member outside of the group requires more complex redesign.*

To support this proposition, Force Flow Diagrams of a stapler are constructed and analyzed. A toy blender design is also analyzed in (Lefever, 1995). From these examples, hypothetical piece combinations are presented for some of the groups.

Stapler Example

An exploded side view of the stapler under study is shown in Figure 4. It consists of twenty four parts, and is indicative of many staplers currently on the market.

The stapler has three sets of operations. Each set has a forward operation and a corresponding reverse operation. The three sets of operations for the stapler are: (1a) when pushed on the top, the stapler extrudes a staple through the front side of a set of papers and bends the staple up into the back of the last page(s), (1b) when released, the stapler springs back into a ready position; (2a) the impact plate can be pushed up and rotated 180^{o} using the swivel button, (2b) and released back into the base so staples can be bent inward or outward into the page; (3a) to insert staples or remove failed staples, the top track can be disengaged with the bottom track by lifting up on the top, and then (3b) re-engaged when completed.

Force Flow diagrams of each of these operations can be individually constructed. For all three, as should be expected when springs are loaded then unloaded, there will be a great deal of redundancy in the diagrams. The flow direction simply reverses once the spring unloads.

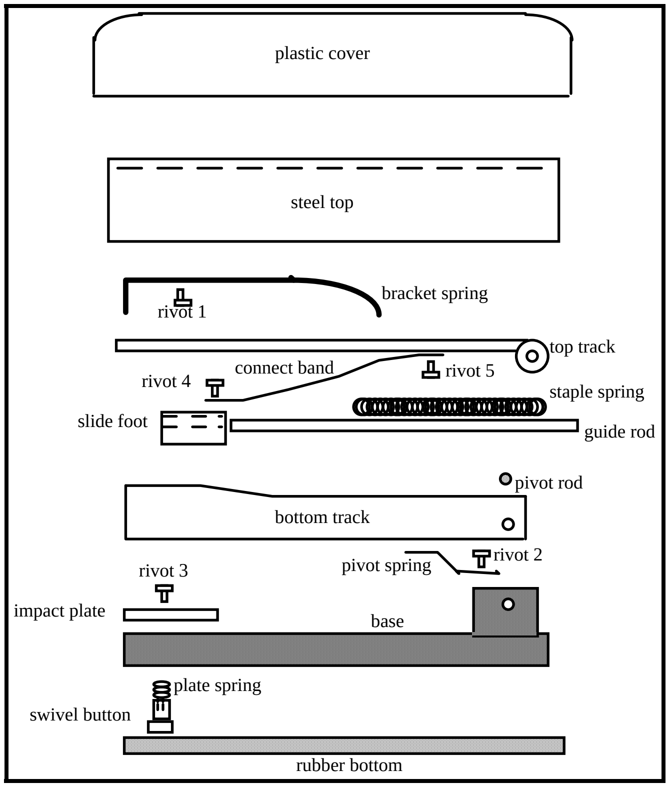

Figure 4: Exploded Side View of Stapler.

For this example, operation (1) is chosen. The hand provides the external force which pushes down on the top. This force is transferred to the spring-bracket, to the top track, to the bottom track, through the pivot spring into the base, and out to an external surface. When the pivot spring is deflected enough, the upward reaction force overcomes the downward spring-bracket force. This force causes relative motion between the spring-bracket and the top and bottom tracks. This motion allows the spring-bracket to begin to push a staple out through the pages and onto the impact plate. In the meantime, the staple spring transfers force to the slide foot and onto the staples. This keeps the front staple in place and moves the next staple up (horizontally) after the front staple has been displaced.

Force flow occurs through all components except three (Figure 5). The connect band and rivets 4 and 5 are integral components for operation (3), but are not needed for operation (1).

Placing "R's" between relative moving components, and grouping them leads to Figure 5. Considering Group 1, it can be conceived that the plastic cover, the steel top, and the rivet could all be combined as one component. This component would be a plastic top with a snap for the bracket-spring to connect.

For Group 2, combination of the staple spring and slide foot could take place by using a spring that could push the staples itself. This modification would simply entail an additional manufacturing operation and parametric changes to the spring.

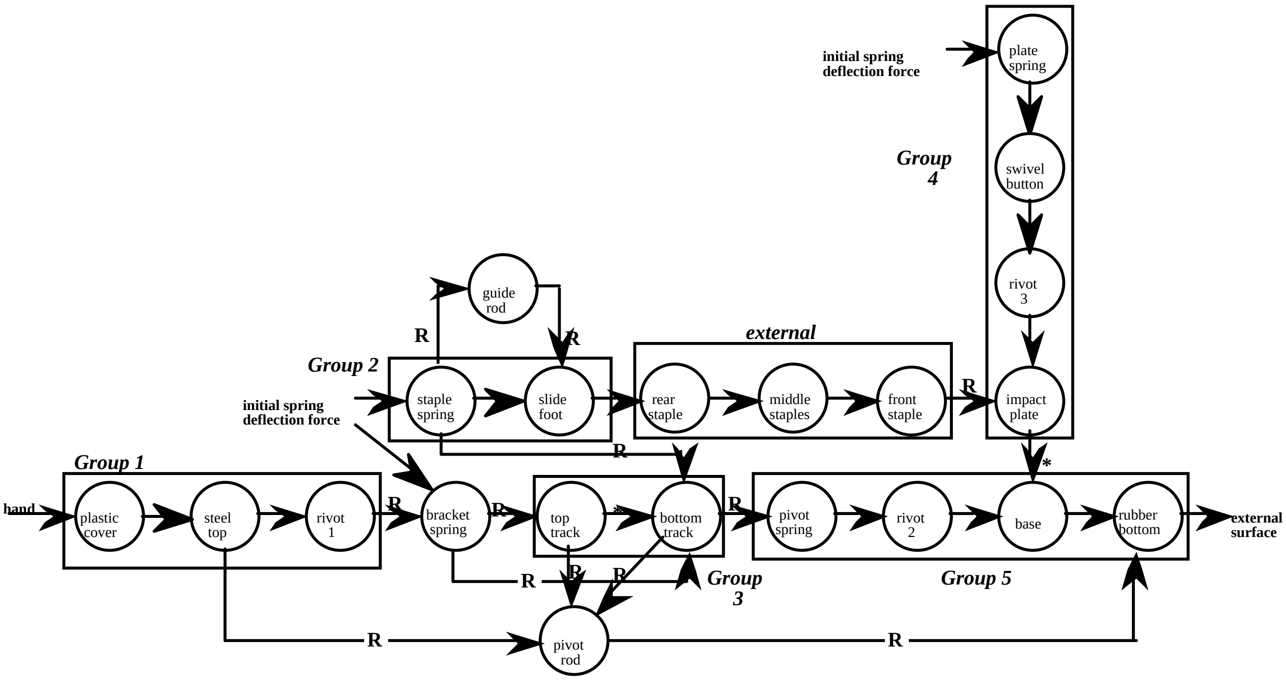

Figure 5. Stapler Force Flow Diagram.

Moving to Group 3, the top track and bottom track could easily be combined. The top track provides the cover for the staples and a surface for the spring-bracket to force down. If the bottom track is enclosed, this combination would eliminate the need for the top track. However, an asterisk is placed between the top and bottom tracks in Figure 5 since these components have relative motion on a Force Flow Diagram for one of the other operations. In this case, it is operation (3): the input or removal of staples through the disengaging of the two tracks. This motion does not mean that it is impossible to combine the top and bottom track as there might exist a design that would eliminate the need for disengaging the tracks.

Examining Group 4, the entire group consisting of the plate spring, swivel button, rivet 3, and impact plate could be visualized as a single component, embodied in Figure 6. Again, the asterisk between the impact plate and base displays relative motion for a different operation. Disregarding operation (2) would lead to the conclusion that there is no relative motion between any of the parts and that they could all be integrated into the base.

The final group is Group 5. It is feasible that rivet 2 and the base could be combined, and the pivot spring be press fitted onto a knob. The pivot spring and the base, however, require different materials as do the base and the rubber bottom. These components would be difficult to combine.

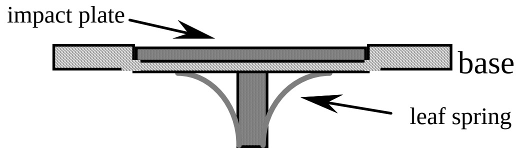

Figure 6. Impact plate redesign.

The examples given for the combination of components in this design are redesigns that could be undertaken without affecting the functionality of other components. Attempting to conceptualize the combining of components outside of their groups means combining pieces that have relative motion. Such combinations require a higher level of redesign that would likely result in the functional alteration of the other components. To visualize this situation, one can conceptualize the combination of the stapler's components that are members of different groups. It is not trivial.

Integration: Force Flow and Reverse Engr.

Figure 1 shows where Force Flow Diagrams integrate into the methodology. Force Flow Diagrams should be constructed after disassembly. In many products, it would be difficult to determine the force transfer between components before the product is disassembled. Step 3 of A Reverse Engineering Methodology is to *Learn and document the actual product function*. This step is where the detailed function structure is generated, relating directly functionality of force flows.

The redesigns resulting from the Force Flow Diagram analysis are component combinations which are usually adaptive types of redesign. Hence, the analysis of the diagrams fit well as a sub-step of Step 9 - *Redesign product subsystems - adaptive design* (Figure 1).

Boothroyd & Dewhurst Extension

The Subtract and Operate Procedure is used to check for redundant pieces and Force Flow Diagrams are constructed and analyzed for piece combination opportunities. These techniques are effective for redesigning a product at a low level. The redesign is either a parametric or a low-level adaptive redesign. To achieve further piece count reduction, a higher level of adaptive design is required. The third technique, the Boothroyd & Dewhurst Extension, is aimed at this type of redesign. This extension is better termed a methodology than a technique as it is more of a guided thought process than a procedure or a model like the two previous techniques.

The Boothroyd & Dewhurst Extension is an evolution of the Boothroyd and Dewhurst theoretical minimum number of parts determination. Again, according to Boothroyd and Dewhurst, a piece must exist if: (1) the part moves relative to other parts, (2) the part must be made of a different material than other parts, or (3) assembly or disassembly of other parts would be impossible if the part was not separate. Thus, each of a product's components will fall under one of the following four cases: (1) the component meets none of the three criteria, (2) the component meets one of the three criteria, (3) the component meets two of the three criteria, or (4) the component meets all three criteria.

The complexity for redesigning to eliminate a component increases in magnitude from case (1) to case (4). Case (1) is where Boothroyd and Dewhurst focus their redesign attention. However, the other cases should not be disregarded. It may turn out that relative movement between two components is not necessary for the functional requirements of the design to be fulfilled. Likewise a design could be altered so that different materials are not necessary or assembly does not rely on a particular component. These are typically more complex redesigns that require a higher degree of conceptualization. However, identifying which components are the focus as well as recognizing the goal of the redesign is important. This is what the Boothroyd & Dewhurst Extension aims to do. It should be used in close accordance with the customer needs and engineering requirements of the design so that functional properties of the design are not lost in redesign.

For the Boothroyd & Dewhurst Extension, the following steps should be used to develop the thought process:

(1) Examine the Force Flow Diagrams.

(2) Analyze within the groups of the Force Flow Diagrams first, then outside of the groups.

(3) Develop a relationship matrix between focal components and indicate the constraints (relative movement, material requirements, and/or assembly/disassembly requirements) between each pair. For components outside of groups (having relative movement), those connected by a force flow should be considered first. They are in physical contact which improves the chance of isolated design changes.

(4) Focus on case (2) pairs first, case (3) pairs second, and case (4) pairs last.

(5) Consult the morphological matrix to determine the function for each component in the pair. This will help to expose why the constraint(s) exist. Then, scan the matrix for other solution principles that could stimulate ideas.

Examining the Force Flow Diagram for the stapler reveals where relative movement between components exists. Relative movement conditions provide the largest obstacles to overcome. Many times, manufacturing techniques can be used to eliminate material and assembly/disassembly constraints. Relative movement constraints more often require functional redesign. For this reason, the groups formed in constructing the Force Flow Diagrams should be the first focus as there is no relative movement between members of a group. For each group, a matrix should be constructed to indicate if a component has no constraints (case 1), or if the component has material constraints and/or assembly/disassembly constraints with another component. Table 2 shows such a matrix for Group 5 of the stapler. A “0” is entered for a no constraint condition between components, an “M” is entered is for material constraints, and an “A” for assembly/disassembly constraints. An “R” is used for a relative motion condition, but in the case of groups, there will not be any “R's". From this matrix only case (2) conditions exist in the form of material constraints. Choosing a pair of components and determining what function(s) they provide is the first step. This analysis will help in understanding why they must be different material types.

Table 2. Boothroyd & Dewhurst Extension Worksheet — Stapler Example.

Component	pivot spring	rivet 2	base	rubber bottom
pivot spring	-	0	M	M
rivet 2		-	0	M
base			-	M
rubber bottom				-

For this example, the pivot spring and the base are chosen. The pivot spring's function is to provide a reaction force to the bottom track which, first, initiates relative movement between the spring-bracket and the tracks so that a staple can begin to be extruded, then second, it returns the entire head of the stapler after stapling has been completed. Searching through a morphological matrix of the stapler would reveal the spring-bracket as a similar solution principle. Is there any way this component could be utilized?

The answer is that they could be combined. Although it would seem very difficult to combine components with relative movement, there can exist relative movement within the combined component. Figure 7 shows a viable redesign of the spring-bracket. The return function of the pivot spring is now carried out by the spring-bracket, with relative motion accomplished by the reaction force of the bottom track on the impact plate, as is common in most staplers.

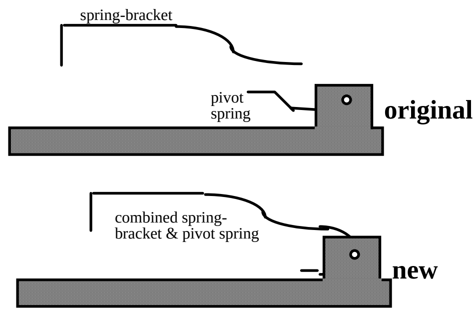

Figure 7. Combined spring-bracket & pivot spring.

Although this redesign suggestion involves combining pieces outside of Group 5, it is the thought process that helped to develop the idea. Attempting to eliminate the need for a different material between the pivot spring and the base leads to the discovery of similar solution principles and ultimately to the above adaptation.

Further examples are possible outside of groups, e.g., the pivot rod and its connecting components. To combine such components, tradeoffs will needed between component geometry (cylindrical), manufacturing operations (stamping), and ingenuity of new solution principles. Lefever (1995) and Ananthasuresh/Kota (1995) give insights into this case.

Integration: Extension and Reverse Engineering

Figure 1 shows where the Boothroyd & Dewhurst Extension integrates into the methodology. Like the Force Flow Diagram analysis, the Boothroyd & Dewhurst Extension fits nicely into Step 9 of the methodology as any resulting redesigns are likely to be adaptive. An important advantage of integrating this technique into the reverse engineering and redesign methodology is that the morphological matrix can be consulted for ideas. This approach is shown in the spring-bracket example as the morphological matrix for the product (column 1) is scanned, and a similar solution principle helped to provide a redesign concept.

3 INDUSTRIAL APPLICATION: SLIDE-OUT AUXILIARY VISOR

An automobile supplier currently manufacturers a slide-out auxiliary visor (SOAV) as a part of a complete overhead unit to a luxury automobile manufacturer. The motivation behind an auxiliary visor is to provide a means of blocking light in the front range for the driver or passenger, while the traditional fold-down visor, in the swiveled position, shields light coming from the side. Most auxiliary visors consist of a second fold down visor. The SOAV, being contained above the headliner, must first translate out, then rotate down to block incoming light. A schematic of the arrangement is shown Figure 8. Figure 9 is the SOAV in the translated position.

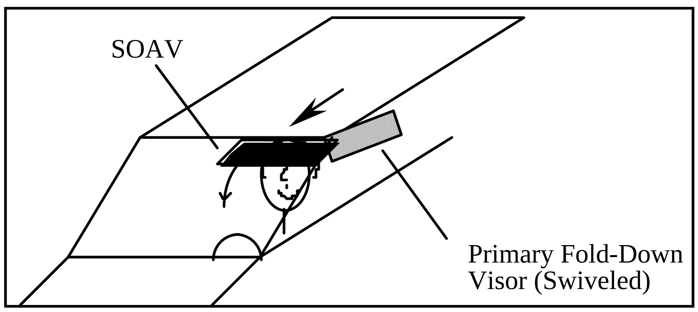

Figure 8. Simple Schematic of SOAV.

The SOAV assembly consists of forty parts. It is a high volume product, so reducing the assembly costs for each SOAV is an important issue. Assembly time can be reduced through easing the handling and insertion of certain components, or by reducing the number of assembly operations. Because forty parts is considered a high quantity of parts for the function that is performed, reducing the number of parts would likely lead to the greatest reduction in assembly times. This reduction in turn reduces the assembly costs.

Figure 9. SOAV in translated position.

The established task is to redesign the SOAV for piece count reduction. The following sections present how the Subtract and Operate Procedure, Force Flow Diagrams, and the Boothroyd & Dewhurst Extension techniques are used in the reverse engineering and redesign methodology to significantly reduce the piece count of the SOAV.

SOAV Redesign

For the SOAV, steps 1-9 of the RE Methodology (refer to Figure 1) are applied. Each step is not documented completely due to space limitations. The reader is referred to (Lefever, 1995) and (Otto and Wood, 1996) for more details.

Step 1: Predict Product Behavior

Step 1 of the methodology is completed before internal inspection of the device. It is a prediction or a hypothesis of the product's behavior. The reason for prediction is so the designer can use his/her skills and intuition to hypothesize the mechanics of the design. Steps 2-5 are the analysis of the actual product as the product is "opened up" and the solutions of the design are seen. Once these are exposed, the mind becomes enamored by the chosen solutions, and difficulties may exist in conceiving alternative solutions. For this reason, it is important to carry out step 1 before disassembling the product — so alternative ideas can be established.

Critical to step 1 of the methodology is the gathering and organizing of customer needs. In developing the customer requirements, all relevant customers must be considered. The following list contains the customers that were identified in forming the customer needs. (a) Consumer — Driver and Passenger, (b) Production customers— Supplier Manufacturing — Automobile Assembly, (c) Marketing/Sales — Supplier Marketing. After carrying out customer interviews, following the procedure outlined in (Otto, 1996; Otto and Wood, 1996), a list of customer needs was assembled and organized as follows: Functional Performance: blocks light, easy to operate, comfort to hold, easy to rotate and translate, ...; Isolation: does not vibrate, does not generate noise, ...; Structural integrity: has long life, stays closed, won’t bend, ...; Interface with overhead unit: hidden overhead, accept handle, ...; Manufacturing: easy to attach to overhead unit, use injection molding and stamping, ...; Appearance: aesthetically pleasing: streamlined, not bulky, ...

Step 2: Disassembly of Product

The disassembly plan and Subtract & Operate Procedure steps are combined to provide the necessary information for the Bill-of-Materials. The following procedure is followed:

(1) In disassembling the SOAV, the strategy is to use two products. One SOAV acts as a reference as the other one is disassembled.

(2) Each part is removed one at a time.

(3) The component is recorded in a Disassembly Process Table in the order it is removed

(4) Once the device is completely disassembled, it is reassembled using the aid of the Disassembly Process Table. This helps to fully understand the correct or best order of assembly, and validate the access direction, necessary tools, and process.

(5) Then, the five step SOP procedure is followed.

Step 3: Learn and Document Actual Product Function

The more generalized subfunctions of the SOAV are decomposed into atomic (finest) level subfunctions. For instance, the "Guide Motion" function is decomposed into "allow linear DOF", "dampen linear motion", and "constrain DOF during translation". These functions provide a basis for a complete functional statement of the SOAV, and motivate the force flow redesign.

Figure 10 shows the Force Flow Diagram for the operation of translating the visor, then rotating it down. The diagram shows a great deal of symmetry with the force flow transfer through the SOAV. A line could be drawn horizontally down the middle and those components above the line would be components that would be found on the inboard side of the SOAV. Those below the line would be components found on the outboard side of the SOAV. The diagram is then a representation which combines function and form.

Steps 6-8: Mathematically Model Product

Analyze Results of SOP in Step 2: The removal of the inboard cable results in no change in the degrees of freedom of the blade. The functions of the cable were identified as constraining a rotational DOF and providing linear resistance (dampening). If the DOF is unchanged when the cable is removed, there might be a redundancy. Checking the subfunction "constrain DOF during translation" exposes that there are two solution principles for constraining the negative SOAV rotation: the inboard cable and the angle of the tracks themselves.

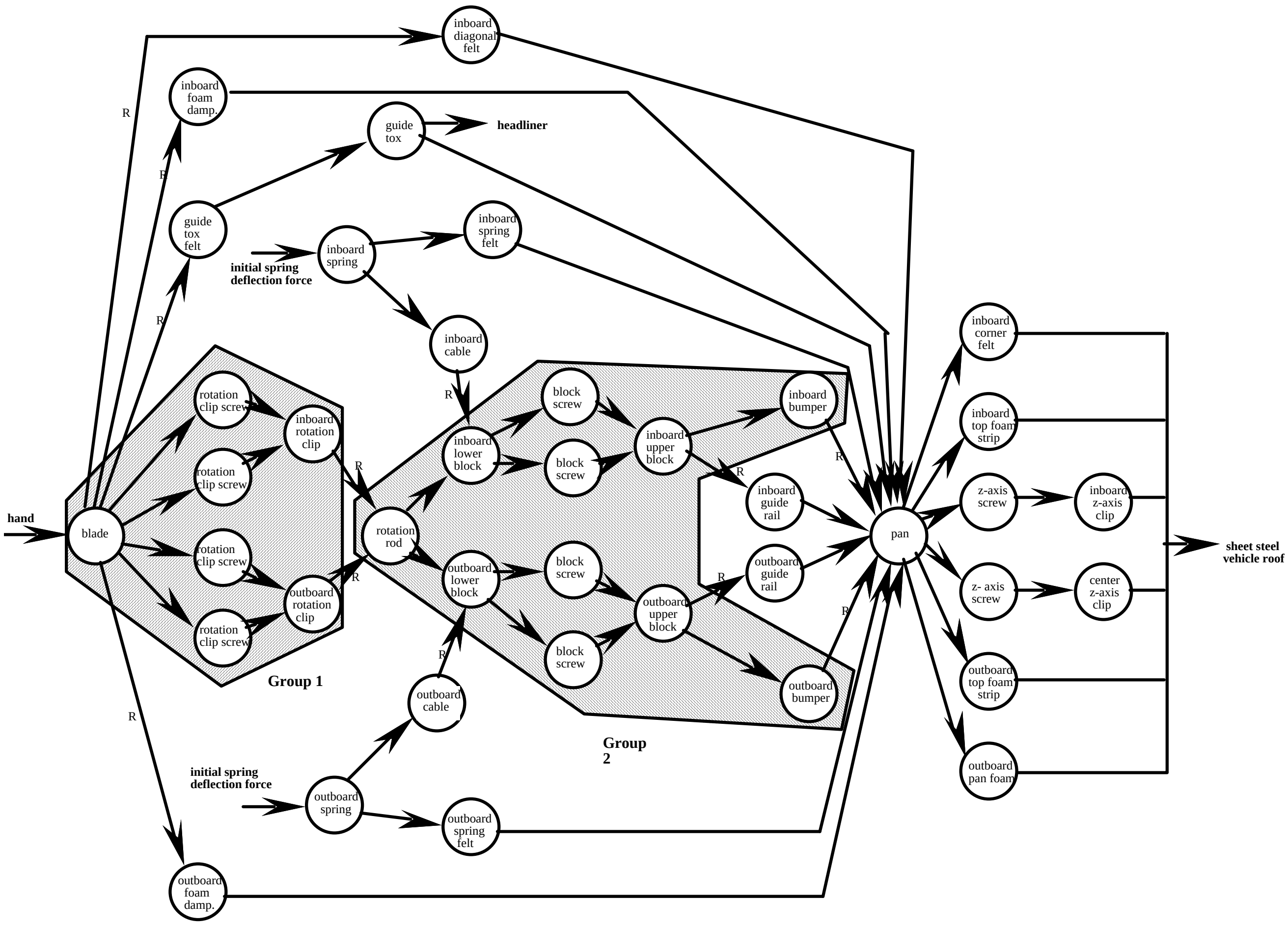

Figure 10. Force Flow Diagram of the SOAV.

Although there is no change in DOF when subtracting the inboard cable, the other function of providing linear resistance is lost, and the effort to pull out the blade is decreased. This means that the cable is not a Type 1 redundant component, but it may be a candidate for a Type 2 redundancy. Type 2 components can have their effect from removal compensated through parametric redesign of other components. The cable's other subfunction, "provide linear resistance (dampening)", is solved by multiple solution principles. Analyzing these solution principles and the components that embody them, the remaining outboard cable can be used to compensate for the loss in linear resistance. Decreasing the length of the cable or increasing the spring constant of the extension spring will increase the cable's tension and provide more friction across the lower slide blocks.

Engineering Model and Mathematical Equations: An assortment of different components could be the focus of a model for the parametric redesign of the SOAV. For instance, the blade geometry could be analyzed to reduce blade flutter, or the rotation clips could be modeled to check the effect of thickness variations on the rotational resistance. Because the objective of this case study is to reduce the piece count of the SOAV, and a Type 2 redundant component has been identified, the friction provided by the cables is the subject of this model.

Figure 11 is a schematic of the cable/spring design. The tension, *T*, in the cables is provided by the springs. The spring deflection is *x*, and the spring constant is *k*. The tension in the cables is the normal force acting across the knobs of the lower slide blocks. The coefficient of friction between the cable and knob is denoted as $\mu_{c,k}$. Thus, the normal force across each knob is equal to *2kx*. And the total friction force is: $friction = 4kx\mu_{c,k}$ (objective function). This friction provides the necessary resistance so that the visor can maintain any linear position while experiencing a specified deceleration. From Figure 12, knowing the mass of the blade and attached components and the deceleration, the required friction can be determined. By summing the forces in the x-direction, the constraint for the frictional force becomes: $4kx\mu \geq ma\cos\theta + mg\sin\theta$

Therefore, it is dededuced that eliminating a cable simply reduces the left side of this equation in half. Parametric compensation can occur by increasing the spring constant, the spring deflection (cable length), and/or the friction coefficient.

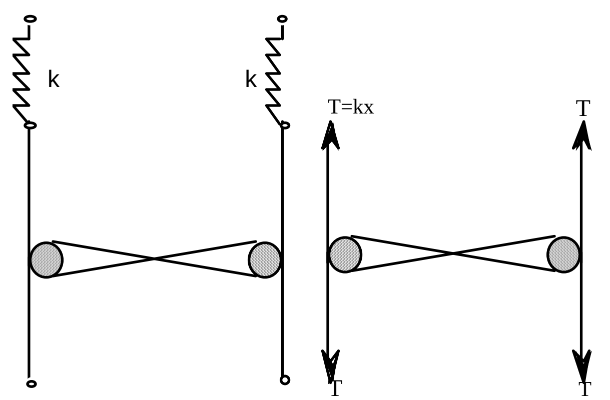

Figure 11: Schematic/FBD of Tension Cables.

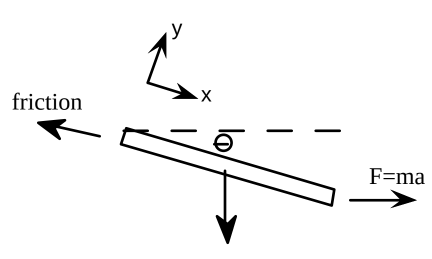

Figure 12: “FBD” of Linear Friction.

Create a Physical Model: Creating a prototype of this parametric alteration is trivial. First, the inboard cable is removed, and the remaining extension spring is replaced with a spring having double the spring constant. Figure 13 shows this alteration.

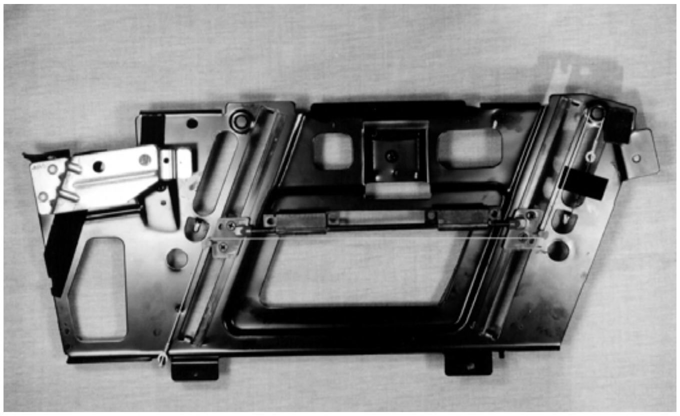

Figure 13: SOAV Single Cable Redesign.

This prototype is then tested for its pull efforts. These efforts are found to be within specification (4.5 - 16 N), and the redesign is validated. Eliminating the inboard cable allows for the elimination of the inboard extension spring and the inboard extension spring felt. Overall, this is a piece count reduction of three parts.

Step 9: Redesign Product Subsystems - Adaptive Design

In Step 3, the Force Flow Diagram for the translation and rotation operation is generated. To analyze the diagram, an "R" is placed between components with relative movement. The components are then grouped. Figure 10 displays two of the groups found in the Force Flow Diagram. The focus of the adaptive design for the SOAV is on Group 2.

Group 2 is symmetrical. The rotation rod connects a series of inboard components and a series of outboard components. Any redesign to one side can be duplicated on the other side. Combining components across the symmetry is difficult. As in the Boothroyd & Dewhurst Extension, a combination chart for one side of Group 2 is shown in Table 4. "M" denotes material constraints, and "A" represents an assembly or disassembly constraint.

Table 4: Boothroyd & Dewhurst Combination Chart for SOAV Group 2.

Components	rotation rod	lower slide block	block screw	block screw	upper slide block	bumper
rotation rod	-	M,A	A	A	M,A	M
lower slide block		-			A	M
block screw			-			M
block screw				-		M
upper slide block					-	M
bumper						-

Examining the table shows that the block screws which join the upper and lower slide blocks could possibly be eliminated through the use of snaps. However, it would be preferable to simply combine the upper and lower slide blocks. The chart shows that there are assembly/disassembly issues involved. The adaptive redesign in Figures 14 shows how this constraint is eliminated so that the two components could be combined. The foam bumper that fit between the upper and lower slide blocks is replaced with an o-ring. The assembly issue is handled by swiveling the block sub-assembly into the tracks. The combination of the upper and lower slide block on the inboard and outboard sides leads to a piece count reduction of an additional six parts.

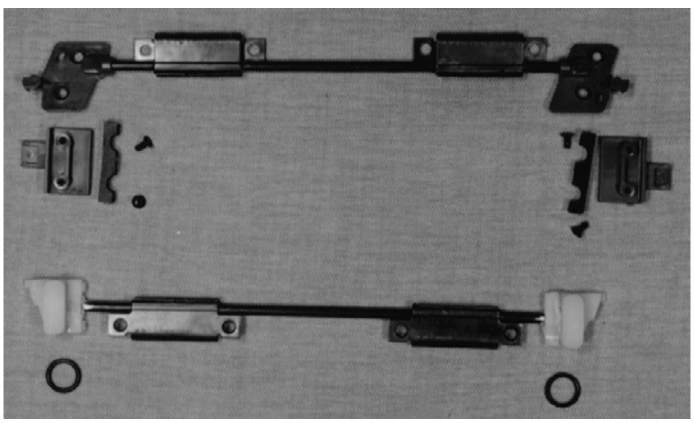

Figure 14: SOAV Present (Top) & New Single Slide Block Redesign (Bottom).

Redesigned SOAV

The established task of reducing the piece count of the SOAV is accomplished through the use of the expanded reverse engineering and redesign methodology (Otto and Wood, 1996). A redesign with a total of nine less components is developed.

Eliminating the cable, extension spring, and spring felt, and purchasing springs with double the spring constant are straight forward adjustments. The supplier has already implemented these changes. Not only did the piece reduction lower the manufacturing and vending costs, but it allowed the supplier to move an assembler off of the SOAV line onto another line. Altogether, the change has translated into a *significant* annual savings for the supplier (actual data cannot be published). The single slide block redesign that eliminates an additional six components is still in the prototype stage. Even with the costs of new insert molds for the single block design, the annual savings from this change are forecast to be of the same magnitude as the cable elimination redesign.

4 CONCLUSIONS

In completing this research, a number of general conclusions are generated. The first conclusion is that Design for Assembly can be evolved from what is currently written and practiced. DFA techniques such as the Boothroyd and Dewhurst manual and Poli's techniques are powerful means for assessing a product's ease of assembly. They are thorough in rating a product so that the efficiency of the design, with respect to its assemblability, can be evaluated. Once the design efficiency is determined, the potential for redesign can be seen. The techniques presented in this report show that DFA can be expanded with basic, simple techniques to link "if a product should be redesigned for piece count reduction" to "how the piece count can be reduced".

The three techniques used to accomplish this are not difficult. The Subtract and Operate Procedure is a very logical process. What better way of figuring out the function of a component than removing it and operating the system without it? Force Flow Diagrams do not require much expertise either. They can be constructed through visual analysis of the product. Determining relative movement between components is usually a trivial matter, so forming the groups is an easy task. The Boothroyd & Dewhurst Extension can be more complicated, but it is based on simple guides for thinking and brainstorming. None of the three techniques is long or tedious. Investing the time to carry them out could expose piece count reduction opportunities that result in large cost savings.

The three techniques seem to fit well into the reverse engineering and redesign methodology. The methodology is roomy, meaning it can accommodate additional techniques. The ten major steps of the methodology establish a foundation. Within these primary steps are open slots in which additional techniques can be placed. If placed into the correct slots, the techniques can feed off the other techniques of the methodology. Where they may be less useful independently, the methodology supports the techniques and makes them more effective.

A final insight produced out of this research is that extensive understanding of a product is hidden. And, until this understanding is revealed, redesign can be misleading. To uncover the hidden understanding, tools are needed to locate then dig in order to reach it. At least a starting point for these tools are the techniques used in the reverse engineering and redesign methodology.

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