Effort flow analysis: a methodology for directed product evolution

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Part count reduction through part combination is a recognized goal of design for assembly (DFA). Some of the many benefits of part count reduction are: a reduced number of assembly operations, reduced procurement costs, cycle time reduction, supply chain reduction, and higher potential profits. In previous work, force flow analysis, a new technique to map forces as they flow across interfaces in a product, was shown to be successful at systematically providing creative insights for part combination. These insights arise by highlighting components having no relative motion between them. This paper presents a novel concept that extends the theoretical basis of force flow analysis to a much broader scope, referred to as effort flow analysis, addressing component combinations having varying degrees of relative motion. A systematic method for classifying these sets of components is given, and compliant mechanisms are presented as an example of successful combinations across interfaces with relative motion. Examples are provided for the redesign of a 'Quick Grip™ Clamp' and a staple remover, both of which highlight a specific class of relative motion components.

Keywords: design methods, product design, component combination, product modelling

Design for manufacturability (DFM) and design for assembly (DFA) can be considered sub-design processes that focus on specific issues (manufacturability and assemblability) within a design. In recent years, DFM has drawn considerable 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.[1] DFM software packages such as computer-aided

1 Kalpakijia, S *Manufacturing Engineering and Technology* Addison-Wesley Publishing Co, New York (1992)

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process planning (CAPP)[1] have provided engineers with tools during the various design stages.[2–6]

Assembly techniques have also received emphasis, as the potential for considerable improvements in product assembly time, and associated profit margins, have helped spread DFA interest into business entities.[7] Even though assembly typically accounts for between 40 and 60% of the overall production time,[8] 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 using robotics and automation.

This trend does not imply that DFA methods are not prevalent. Boothroyd and colleagues published their product design for assembly manual in 1982.[9–11] This manual is regarded as the pioneering work of DFA techniques. It is composed of a formalized systematic approach that includes selection of the assembly method—manual, high-speed-automatic, or robotic assembly—then an analysis of the assemblability of the design using a design for assembly Worksheet. The worksheet (or associated software product) takes into account factors such as handling time, geometries, insertion time, and theoretical minimum number of parts to give an evaluation of the 'design efficiency' of the product. Besides Boothroyd and Dewhurst, many other DFA techniques have contributed to the field and this research.[12–19]

Component combination is one DFA approach to improved assemblability. Component combination (or 'piece count reduction') is the combination of once separate parts into a single piece, which decreases the number of parts that compose a product while maintaining the essential functionality of the product. This piece count reduction in many cases is the most effective means of improving assemblability. Fewer parts imply fewer operations, less handling, and quicker assembly. Piece count reduction can also have broader implications. For example, Douglas Commercial Aircraft Co. ran simulations to determine what drives the cost of their commercial airframe construction. They discovered that in addition to the costs of assembly, the costs of fabrication, quality assurance, overhead-inventory levels, tracking, and purchasing all depend on piece count.[20] Application of piece count reduction techniques is not without its detractors, and it may be possible to go too far in combining components thus increasing the complexity of the product and or assembly, and driving up costs.

Several authors have addressed the area of product complexity different viewpoints.[21–23], Boothroyd et al.[11] proposed a set of DFA guidelines

2 Ullman, David G *The mechanical Design Process*, 3rd McGraw-Hill Book Co, New York (1992)

3 Dixon, J R and Poli, C *Engineering Design and Design for Manufacturing* Field Stone Publishers, Conway, MA (1995)

4 Ulrich, Karl T and Eppinger, Steven D *Product Design and Development* McGraw-Hill, Inc, New York (1994)

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7 Tatikonda, Mohan V 'Design for assembly: a critical methodology for product reengineering and new product development' *Production & Inventory Management Journal* Vol 35 No 1st Quarter (1994) 31–38

8 Andreasen, Myrup M *Design for Assembly* IFS Ltd, UK (1983)

9 Boothroyd, G, Poli, C and Murck, L *Automatic Assembly* Marcel Dekker, New York (1982)

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

11 Boothroyd, G, Dewhurst, P and Knight, W A *Product Design for Manufacturing* Marcel Dekker, New York (1994)

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15 Ishii, K, Juengel, C and Eubanks, C F 'Design for Product Variety: Key to Product Line Structuring' in Proceedings of ASME DETC '95, Boston, MA (1995)

16 Defazio, T L and Whitney, D E 'Simplified generation of mechanical assembly sequences' *IEEE Journal of Robotics and Automation* Vol RA-3 No 6 (1987) 640–656

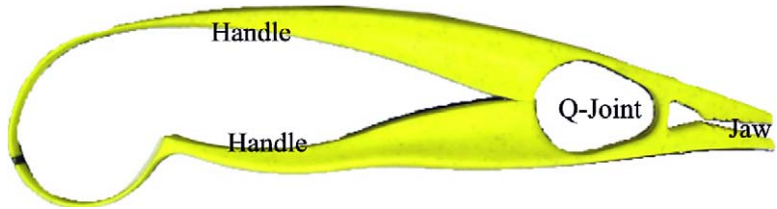

Figure 1 Compliant pliers (ComPlier™)

for component combination. '…the theoretical minimum number of parts represents an ideal situation where separate parts are combined into a single part unless, as each part is added to the assembly, one of the following criteria is met:

(1) The part moves relative to all other parts already assembled during the normal operating mode of the final product. (Small motions which can be accommodated by elastic hinges do not qualify.)
(2) The part must be of a different material than, or must be isolated from, all other parts assembled (for insulation, electrical isolation, vibration damping, etc.).
(3) The part must be separate from all other assembled parts, otherwise assembly, or parts meeting one of the above criteria would be prevented.'

These guidelines form a set of conditions that direct design efforts in part combination, and are based on extensive studies of products and their corresponding assembly processes.

While significant insight is gained from the DFA guidelines, it is proposed here that the first of these guidelines is overly constraining. According to the first guideline, interfacing components having relative motion are thought to be either un-combinable, or require significant redesign for successful combination. Recent 'compliant' mechanism examples bring new focus to the possible combination of parts that experience relative motion. One proposal is that parts having relative motion can be combined into monolithic mechanical devices using jointless compliant mechanisms.[24] The 'ComPlier™' (Compliers Inc., Rolla, MO) is an example of a commercially available device of this type (Figure 1). The device is a plier designed and constructed using compliant joints in place of the traditional kinematic joints.[25]

The ComPlier™ compliant mechanism, molded as a single piece of material, replaces an assembly of multiple components that required relative motion to perform the product function(s). In this case, significant

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19 Kim, G J and Bekey, G A 'Combining assembly planning with redesign: an approach for more effective DFA' in Proceedings of IEEE Conference on Robotics and Automation (1993) p 319
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21 Hinckley, Clifford M *A Global Conformance Quality Model: A New Strategic Tool for Minimizing Defects Caused By Variation, Error, and Complexity* Stanford University (1993)
22 Fagade, A A and Kazmer, D 'Optimal component consolidation in molded product design' in Proceedings of ASME DETC DTM, Las Vegas, NV, September (1999) pp 255–265
23 El-Haik, B and Yang, K 'Measures of Complexity in Design' in Proceedings of DETC DTM, Las Vegas, NV, September (1999) pp 1–11
24 Ananthasuresh, G K and Kota S 'Designing compliant mechanisms' *ASME Mechanical Engineering* Nov. Vol 117 No 11 (1995) 93–96
25 Salamon, B A, and Midha, A 'An introduction to mechanical advantage in compliant mechanisms' *Journal of Mechanical Design* 120 June 120 (1998) 311–315

redesign effort and/or experience was needed to accomplish the part combination as the design of this mechanism required a departure from the original spatial layout, or topology, of 'components,' of the multi-part device. However, it seems possible that certain parts of complex products could be redesigned using the original topology and geometric features by directly replacing certain components with a single compliant component. In these cases, only minor shape modifications and material property issues need to be considered to successfully accomplish the part combination. Therefore, techniques that aid in redesigning a product for piece count reduction are needed. This paper presents a method for identifying this type of opportunity through application of a technique known as effort flow analysis. Effort flow analysis is a systematic tool used to guide the designer toward piece count reduction through part combination. The layout of the present work is first to review the origins of effort flow analysis, then show how effort flow analysis can be used to identify creative opportunities for part combination in complex assemblies where relative motion exists between components.

1 *Background on effort flow analysis*

1.1 *Essential elements*

Effort flow analysis encourages evolution in products from the mechanical energy domain by identifying component combination opportunities that are achievable using rigid body and/or compliant mechanisms. Effort flow analysis is the evolution of a technique originally known as force flow analysis.[6,27–29] In order to be consistent with current and future research efforts in this area, the term *effort flow* is used to replace the original term *force flow*. The change in terminology from *force* to *effort* is the result of a broadened research scope coupled with the fact that in the systems modeling domain, *effort* generally implies a broader class of physical phenomenon than does *force*. Effort flow analysis uses an effort flow diagram to represent the transfer of effort through product components. The effort flow diagram is a semantic network composed of nodes and links that are described using the fundamentals of graph theory.[30,31] The nodes of the diagram represent the components of the product, while the links represent the interfaces between the components.

Whenever possible, effort flow diagrams are laid out in such a manner that the general topology of the product is depicted in the topology of the diagram. As an example, an effort flow diagram for the Quick Grip™ Clamp product (Figure 2) is shown in Figure 3. The main benefit of modeling a product using an effort flow diagram is the exposure of possible component combination opportunities. These opportunities are made more

27 **Lefever, D** 'Integrating design for assemblability techniques and reverse engineering' Master's thesis, The University of Texas, Department of Mechanical Engineering, 1995

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29 **Wood, K L and Otto, K L** 'A reverse engineering and redesign methodology' *Research in Engineering Design* Vol 10 No 4 (1998) 226–243

30 **Harary, F** *Graph theory* Addison-Wesley, Reading, MA (1969)

31 **Tsai, L** *Mechanism Design: Enumeration of Kinematic Structures According to Function* CRC Press, Boca Raton, FL (2000)

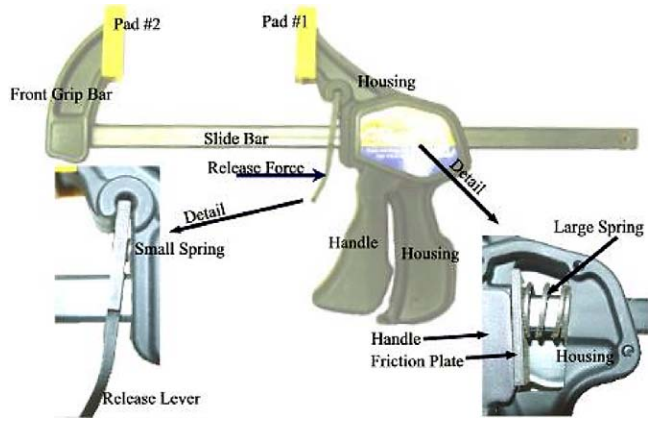

Figure 2 Schematic of the Quick Grip™ Clamp

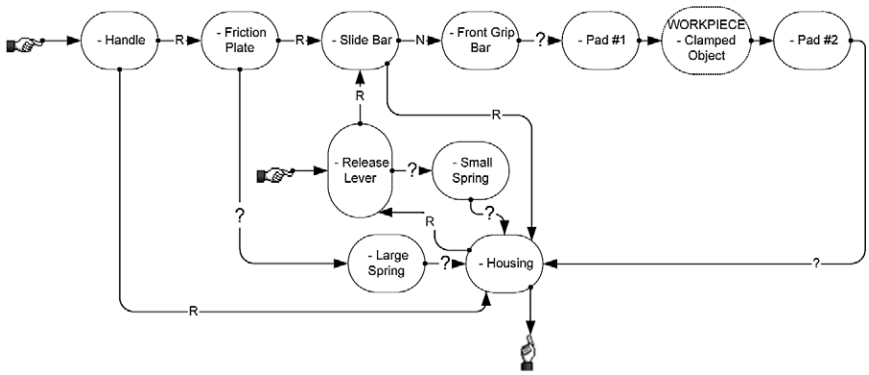

Figure 3 Effort flow diagram for the Quick Grip™ Clamp

obvious when the relative motion at the interfaces between *connected components* is characterized. Characterizing the relative motion entails labeling the links between components. The links model the interaction between components, and are the conduit for effort flow (force or torque transfer in the mechanical domain). Labels are added to the links to identify relative motion characteristics across the link. The labels on links between connected components were previously defined as follows:[26]

‘N’: no relative motion between components.
‘R’: relative motion at the interface and between other regions.

26 Jensen, D D et al. ‘Force flow analysis: opportunities for creative component combination. Recent advances in design for manufacture’ in Proceedings of the ASME International Mechanical Engineering Congress, Orlando FL (2000)

More explicitly, the ‘R’ label is used to denote an interface where ‘relative motion occurs both between the extents of connected components as well as at the physical interface between the components (i.e. the nodes).’ Once

characterization of relative motion and link labeling is completed, the following guideline applies:[6,26–29]*Effort flow guideline*: groups of components where no relative motion exists (no R-Links connecting members within the group) are candidates for combination if not prohibited by material or assembly/disassembly issues. Combination between components or component groups that are connected by R-Links may be possible,

but will require more complex redesign.This guideline suggests the relationship between effort flow analysis and the DFM guidelines of Boothroyd et al.[11] presented earlier, but goes a step further in suggesting that parts that do experience relative motion may still be candidates for combination. The next step in constructing an effort flow diagram is to identify groups of components connected by non-relative motion links (N-Links). These groups of components are the starting point for further investigation of component combination.

1.1.1 Example: effort flow analysis for the Quick Grip® Clamp

A motivating example of effort flow analysis is given in this section and is used for comparison purposes as advancements to the method are introduced. The device modeled is a Quick Grip™ Clamp (American Tool Companies, Inc.). A schematic of the device is shown in Figure 2, while the effort flow diagram is given in Figure 3.

The clamp device works by applying pressure from the hand to the 'Handle' which ultimately closes the two 'Pads' on the object being clamped. Once the 'Pads' are clamped down on the object, they are constrained from moving apart by friction and binding between the 'Release Lever' and the 'Slide Bar'. In order to release the object, a force is applied to the 'Release Lever' in the direction illustrated by the 'Release Force' arrow. The force pivots the 'Release Lever' in the 'Swivel Notch' and releases the friction between the 'Slide Bar' and the 'Release Lever.' In order for the required friction between the 'Release Lever' and the 'Slide Bar' to be maintained during clamping, the 'Small Spring' exerts a small force on the 'Release Lever' in the opposite direction from the 'Release Force' arrow. This 'Small Spring' also provides a force to return the 'Release Lever' to its clamping position ('Release Lever' rotated counter clockwise in the 'Swivel Notch') after the clamp force is released.

The effort flow diagram for the Quick Grip® (Figure 3) shows which components have relative motion between them, and which components do not. A historical definition of relative motion is: motion between two connected components where that motion occurs either at the interface,

away from the interface, or both, during the operation(s) of a device. Analysis of the effort flow diagram and the operation of the clamp demonstrates an interesting phenomenon concerning relative motion. In the case of the R-Links, relative motion occurs between the components with respect to all points on them, including the interface. However, for the components connected by the '?-Links' in Figure 3, relative motion occurs at all points, *except* the interface. For example, the figure shows that the link connecting the 'Small Spring' and the 'Release Lever' is designated with a question mark. As represented by this link, the component motion is a combination of non-relative motion at the contact interface and relative motion at all other points of the two components. For this example, the *ends* of the springs do not experience relative motion with respect to the adjacent parts because they maintain non-sliding contact with those parts. However, the non-contacting portions of the springs *do* experience relative motion with the adjacent parts during operation of the device. Analysis of the remaining '?-Links' produces similar results.

The '?-Links' for this case raise an important theoretical and pragmatic issue. The theory of effort flow analysis presented in Ref.[26] would not assign an R-Link label to the indeterminate links because, by definition, relative motion must exist at an interface to warrant an R-Link. Yet, for the Quick Grip®, the functionality of relative motion is apparent between these components, just not at the interfaces. The fundamental insight from this analysis is that relative motion needs to be defined more precisely to obtain a better understanding of component combination possibilities.

Besides the need to refine our relative motion concept, careful inspection of Figure 3 leads to another dilemma that is common to many product architectures, i.e. the presence of a high percentage of components with R-Links in the figure. If we seek to significantly affect part count in this product, effort flow analysis must include techniques for combining components across R-Links. It is thus apparent that the DFM guidelines of Boothroyd et al.[11] and the effort flow analysis guidelines presented earlier are limited in their applicability and in need of extension. The next section treats this issue and others.

2 *Theoretical advancements in effort flow analysis*

2.1 *The overall effort flow analysis methodology*

The overall effort flow analysis process is graphically represented by the flow chart shown in Figure 4, and is aligned with the product design framework presented in Ref.[6]. The process begins with establishment of the evolutionary goals of the design effort, the goals may be to incrementally

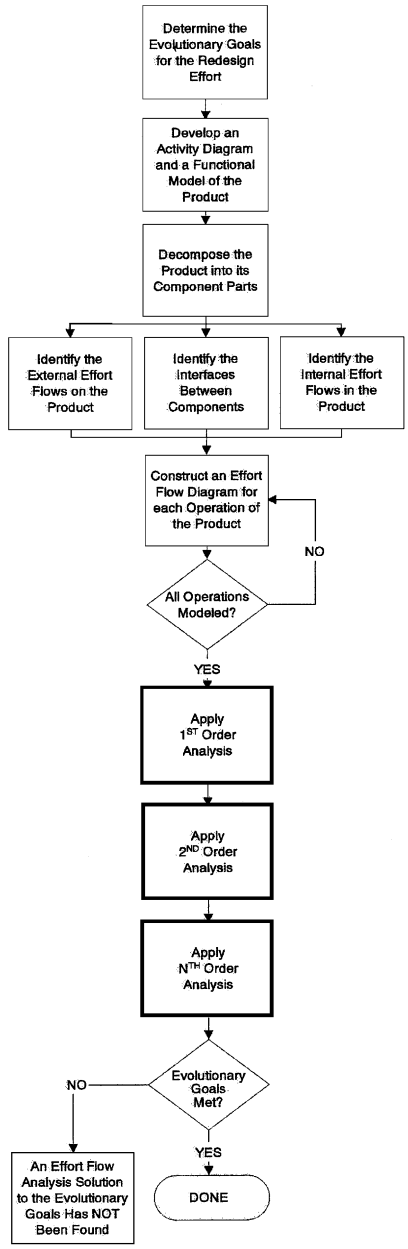

Figure 4 Overall effort flow analysis methodology diagram

evolve the product or they may be to revolutionize the product. It should be noted that the design effort could be to analyze an initial design for improvement prior to a production decision, or to evolve a product under redesign. The process continues with the development of an activity diagram for the product. The activity diagram[6] provides an understanding of

the user operations that the product must carry out; these operations will be modeled in the effort flow diagram. The next step in the process is functional modeling,[6] followed by product decomposition to establish the individual components and their interfaces.

Finally, the components and interfaces of the product are modeled using an effort flow diagram. This is where potential component combination opportunities are identified. These opportunities become apparent during characterization of the relative motion at the component interfaces. Interface characterizations; coupled with the structure of the graph, lead the designer to apply particular design evolution guidelines, which are classified as first through *N*th order. In order to determine when application of a guideline leads to achievement of a successful component combination, a set of criteria are necessary.

2.2 Solid mechanics criteria for successful component combination

Implicit in the effort flow analysis methodology of Figure 4 is the assumption that any redesigned product must continue to satisfy the original product functions. In addition, fundamental physical laws must be satisfied. It is proposed that three fundamental functional criteria, based on fundamental physical laws, form a set of necessary conditions for component combination in the mechanical energy domain.

The three solid-mechanics laws that form the basis for the fundamental functional criteria, and are given as follows:

(1) Strain–displacement law,
(2) Stress–strain law (material constitutive relationship),
(3) Equations of equilibrium (force or stress).

These three laws are intrinsic to the physics of mechanical efforts and are inviolable in all cases, as they completely define the state of the material in the product.

The necessary functional conditions proposed for component combination are as follows:

(1) *Degree-of-freedom condition*: the original degree-of-freedom based functions must be maintained in the resulting combined component, rigid or compliant.
(2) *Energy transmission condition*: the material of the combined component must satisfy the energy transmission functions required for the product.

(3) *Actuation force condition*: the actuation force of the resulting rigid or compliant mechanism must be within the reasonable and achievable bounds of the actuating component.

These three functional conditions represent necessary, but not sufficient, conditions for component combination. Sufficiency is not achieved because the conditions do not capture the full spectrum of possible functional requirements. The relationship between the physical laws and the functional conditions is not one-to-one. Rather, the relationship is best represented as a system of relationships that must be satisfied.

The degrees-of-freedom condition is based on the premise that if motion is provided in the original components, the motion-based function of those components must be preserved in the redesigned component. For mechanisms, the motion has two fundamental requirements, the first is path generation, and the second is end-point positioning.[32] The equilibrium and the strain–displacement (especially for compliant mechanisms) laws are critical in satisfying this condition.

The energy transmission condition is based on the concept of *energy flow* from functional modeling.[6,29,33] In the static or quasi-static mechanical energy domain model used in effort flow analysis, *energy flow* is represented as either forces or torques. Based on this model, efforts will flow through the material of combined components derived from effort flow analysis, and the material strength of these combined components must be sufficient to provide the 'transmit energy' function. This strength criterion necessitates invocation and satisfaction of the stress–strain law.

The actuation force condition is a bounding relationship where the force has a minimum for sensitivity reasons and a maximum for achievability reasons. Equilibrium and strain displacement laws are again critical.

2.3 Importance of relative motion

It is stated in the DFM guidelines proposed by Boothroyd et al.[11] and again in this work, that the absence of macro scale relative motion is a marker for component combination opportunities. It is proposed here that the *existence* of relative motion in varying degrees is *the primary indicator* of component combination opportunities in effort flow analysis. This hypothesis is supported by observations about the importance of relative motion in both physical systems modeling (bond graphs based) and functional modeling.

In modeling energetic physical systems, power is the entity of primary

32 Erdman, A G, Sandor, G N and Kota, S *Mechanism Design: Analysis and Synthesis*, Vol 1, Prentice Hall, New Jersey (2001)
33 Pahl, G and Beitz, W *Engineering Design: A Systematic Approach* Springer-Verlag, London (1989)

interest. Power is the product of effort and flow, where effort equates to force or torque, and flow equates to velocity, as described by power flow theories such as bond graphs.[34] In functional modeling, the three flows are energy, material, and information.[32] In the mechanical domain, modeling of the energy flow requires, at a minimum, the presence of a force and may include a velocity as well. In representing the mechanical domain using either the power flow of a bond graph or the energy flow of a functional model, the fundamental variables are force (or torque), and velocity.

Like power flow analysis and functional modeling, effort flow analysis in the mechanical domain focuses on the flow of effort (force or torque) through the product of interest. The presence of effort in a mechanical product is invariably accompanied by relative velocity between components during some aspect of product operation. The presence of effort is a fundamental requirement for effort flow analysis, while the presence of relative velocity is not. However, the presence of relative motion is critically important from the standpoint of highlighting the locations of interesting interactions between components in the system.

Relative motion identifies locations within the product model where something interesting is happening. Relative motion represents an easily identifiable characteristic of the interaction between the components of the product, and provides a convenient classification scheme for components and interfaces within the mechanical domain.

2.4 *Basis set for relative motion*

As evidenced by the 'R-Links' and '?-Links' in Figure 3, there are several ways that relative motion can occur between components, and effort flow analysis must be able to model each of them. To accomplish this modeling task, we must first establish a fundamental understanding of the elements that make up effort flow analysis. The three fundamental physical elements of an effort flow diagram are the components, the interfaces between the components, and the forces transmitted between components at the interfaces. Table 1 captures the permutations of possible relative motion with

Table 1 Table of relative motion permutations

Link type	*Relative motion location*	
	Between interfaces	*Between components*
N-Link	0	0
C-Link	0	1
R-Link	1	1
I-Link	1	0

34 **Karnopp, D C, Margolis, D L and Rosenberg, R C** *Systems Dynamics: A Unified Approach*, 2nd Wiley Interscience, New York, NY (1990)

respect to components and their interfaces as well as the naming convention adopted to describe each permutation.

Because this set spans all possible combinations of relative motion in the mechanical domain, and because the members of this set are orthogonal, we will refer to the set as a relative motion basis in effort flow analysis. Four flow links are now possible. We define these links between connected components as follows:

‘N-Link’: no relative motion between components.
‘C-Link’: relative motion between the non-interfacial regions of components.
‘R-Link’: relative motion at the interface and between other regions.
‘I-Link’: relative motion at the interface only.

This new characterization of relative motion leads to a more refined set of criteria for investigating component combination possibilities.

The component combination opportunities that can be highlighted using the relative motion characterization just developed are discussed in the next section. The sections are divided by link type, where the link types are further classified as first through *N*th order based on the likelihood of a successful component combination. Where the first-order are the most likely, and *N*th-order are the least likely to lead to successful component combination.

2.4.1 The non-relative motion link: ‘N-Link’ (O^1)

Groups of components connected by N-Links are first-order (O^1) candidates for combination. A N-Link represents interaction between components where there is no relative motion between components and no relative motion at the interfaces. These groups of parts move as a rigid body, and represent the simplest opportunities for component combination. The interface between a rivet and the two pieces of sheet metal that it fastens together is an example on an N-Link. Components grouped in this manner automatically satisfy the relative motion component combination criteria of Boothroyd et al.[11] discussed earlier.

N-Link Guideline: If the interaction between two components can be represented by a N-Link, those components may be combined directly. N-Linked components typically provide the following functions: transmit effort, allow DOF for assembly, and material-based functions such as resist loads or transfer heat. Combination is

contingent upon the satisfaction of the material and assembly/disassembly functions. Assuming these are satisfied, the primary performance function for the combined N-Link component is to transmit effort.

Guideline support: groups of components connected by N-Links are classified as first-order because they represent one of the fundamental tenets of the DFMA approach to component combination presented by Boothroyd et al.[11] and espoused by many noted authors in the field of mechanical design theory.[6,13,14,20,21] Application of the N-Link guideline provides the highest likelihood of success with the least impact on product function and mechanical properties. This is true because, by definition, no relative motion can exist across the N-Link. Hence, the N-Link guideline is applied first before further effort flow analysis is carried out.

2.4.2 *The component relative motion link: 'C-Link' (O^2)*

Groups of components connected by C-Links are second-order (O^2) candidates for combination. A C-Link represents interaction between components where there is relative motion between the non-interfacial regions but no relative motion at the interfaces. This interaction implies deformation of one or more components as force is transmitted. The interface between a coil spring and the spring perch, or perches, on which it rests is an example of a C-Link. C-Links may represent either elastic or plastic behavior in the interfacing components.

C-Link Guideline: If the interaction between two components can be represented by a C-Link, those components can be combined directly into a compliant mechanism by making parametric changes to the geometry of the components involved. C-Linked components typically provide the following functions: transmit force, store/supply energy, allow DOF, and material based functions such as secure solid and inhibit energy.

Combination is contingent upon satisfaction of the material and assembly/disassembly functions, as well as functional relationships to include the necessary deformation and/or energy storage properties provided in the original product design. Assuming these are satisfied, the primary performance functions for the combined C-Link component is to allow DOF, transmit force, and store energy.

Guideline support: groups of components connected by C-Links are classified as second-order (O^2) candidates because they represent a reduced likelihood for successful component combination when compared to the more fundamental approach of the N-Link combination. The presence of a C-Link implies that an intended relative motion function(s) exists in the original components. Component combination has the potential to impact these deformation based product function(s), and hence the likelihood of produc-

ing a successful combination using compliant components is high, as compliance is used in the original design. However, satisfaction of the three necessary functional conditions is typically more difficult to ensure simply due to the presence of relative motion.

The integration of two parts connected by a C-Link necessitates that the material and/or geometry of the combined part have properties that provide the deformation/return functions originally performed by the separate deformable part while providing the support functions of the interfacing support component. In addition to the deformation requirement, the material used in the combined component must have specific material properties related to other functional requirements such as color, creep resistance, conductivity, weight, etc. required in the original design. The greater the number of functional requirements, the greater the material selection challenges become.

2.4.3 *The relative motion link: 'R-Link'(O^N, Nth order)*

Groups of components connected by R-Links are *N*th-order, three or higher (O^N), candidates for combination. A R-Link represents general relative motion occurring both at the interface and between the extents of the components as force is transmitted. The hypothesis that R-Links are 'combinable' only through significant redesign effort is modified here to reflect the fact that the level of effort required to achieve component combination across some R-Links is not as significant as originally thought. R-Links take many forms to include: kinematic joints of all kinds, sliding contact in slots and guides, gears, and bearings. R-Links may also represent the interface between a compliant member and a support member if that interface is not fixed.

R-Link Guideline: if the interaction between two components can be represented by a R-Link, those components can be combined directly into a compliant mechanism provided the original relative motion function can be provided through deformation of the combined components. R-Linked components typically provide the following functions: allow DOF and transmit force, and the primary material based function is to regulate friction.
Combination is contingent upon satisfaction of the material and assembly/disassembly functions, as well as functional relationships to include the necessary path generation and end point positioning properties provided in the original product design. Assuming these are satisfied, the primary performance functions for the combined R-Link component is to allow DOF and to transmit force.

A first cut at synthesis of the combined component is to fuse the components using their original material and geometry, then make parametric changes to refine the combination.

Guideline support: groups of components connected by R-Links are classified as *N*th-order, three or higher (O^N), candidates because they represent the least likelihood for successful component combination when compared to the N-Link and C-Link combinations. In essence, the solid mechanics criteria discussed above give the defining guidance on component combination across R-Links. These criteria may be difficult to satisfy as the magnitude or spatial displacement of the relative motion increases.

2.4.4 *The interface relative motion link: 'I-Link'*

An I-Link represents relative motion at the interface only. No relative motion exists within the extents, i.e. non-interfacial regions, of the components (Table 1). While clearly a member of the basis set, this link has not appeared in any of the products evaluated in our research, either conceptually or within our empirical studies of products. For this reason, further discussion of the I-Link will be set-aside. As we study other energy domains, beyond mechanical, the I-Link type of relative motion may become apparent.

2.5 *Product modeling using relative motion basis (O^3 or higher)*

The effort flow analysis advancements just discussed, combined with previous work,[26] results in a method powerful enough to be applied early in the design effort where significant impact can be achieved. Early application is possible because the information needed to use the method is not highly detailed. At this point, an example is in order. To illustrate effort flow analysis, an example that exhibits all three classes of links known to exist in the mechanical domain is chosen.

The example is found in the Quick Grip® Clamp (see Figure 2). An effort flow diagram, Figure 5, is constructed using the full relative motion basis. Note that the links previously labeled as ?-Links (those on both sides of the two springs and pads) in Figure 3 are now labeled with C-Links. Using the proposed extension of effort flow analysis, the 'Small Spring' is more appropriately connected to both the 'Release Lever' and the 'Housing' by a C-Link, as are the interfaces for the pads and for the large spring.

Applying the C-Link guideline leads to the potential combination of the 'Front Grip Bar' and 'Pad #1,' while application of the C-Link guideline to the 'Small Spring' and either of its neighboring parts leads to a potential combination as well.

Assume that the decision is made to combine the 'Small Spring' with the 'Housing' to produce a compliant region of the housing that satisfies the

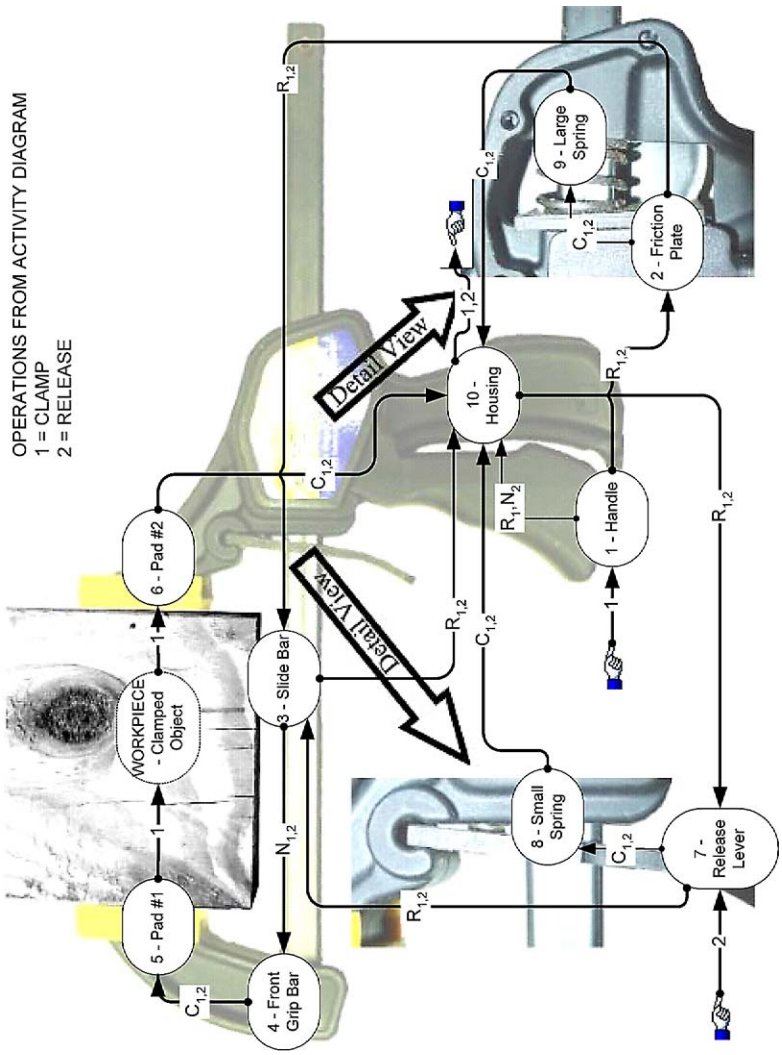

Figure 5 Enhanced effort flow diagram for the Quick GripTM Clamp

functional requirements of the spring. With this decision as the starting point, the solid mechanics criteria are now employed.

1. The position of the lever determines the position of the spring and the engagement of the lever with the bar. The motion of the lever is rotation about the interface notch in the housing. The lever has a single DOF, and that DOF must be maintained for product function reasons. By choosing to combine the spring and the housing, and not the spring and the lever, the DOF of the lever is unaffected by the combination.

2. The force transmission and strain energy storage functions of the spring relate to transmission of the finger force to the housing, and storage of potential energy to restore the release lever to its original position. These energy transmission functions must be provided without causing material failure in the now combined spring/housing.

3. The actuating entity is the finger of the operator. The maximum human effort can be determined from anthropomorphic data. The minimum force is determined by the amount of preload required to maintain sufficient friction between the release lever and the slide bar to initiate locking during the clamping operation.

Satisfaction of these functional criteria will dictate that at a minimum the three laws from solid mechanics (strain/displacement, constitutive, and equilibrium) be applied to the analysis of this combined component. Clearly there are material and geometry decisions to be made, the point of this example is to show the power of these simple guidelines to highlight opportunities and give simple guidance for systematic evolution of the product. To determine the potential benefit of this combination, assembly and tooling costs, as well as issues of weight and aesthetics of the combined part would need to be evaluated.

2.6 *Comprehensive example*

A more comprehensive example of product evolution through component combination is demonstrated for a staple remover product. The original version of the staple remover has ten parts as shown in Figure 6. The effort flow diagram for this product is shown superimposed on an image of the product in Figure 7. Using effort flow analysis, the part count may be significantly reduced in the device. In fact, sequential application of the link guidelines suggests that the device can be reduced to a single part. This piece count reduction process begins by combining the parts in group 1 and in group 2 of Figure 7. As these groups contain only N-Links, parts within the groups may be directly combined with no loss of relative motion functions.

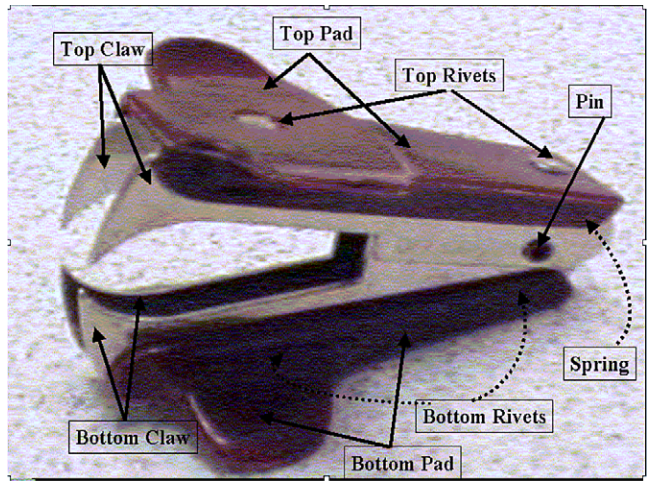

Figure 6 Schematic for the staple remover product

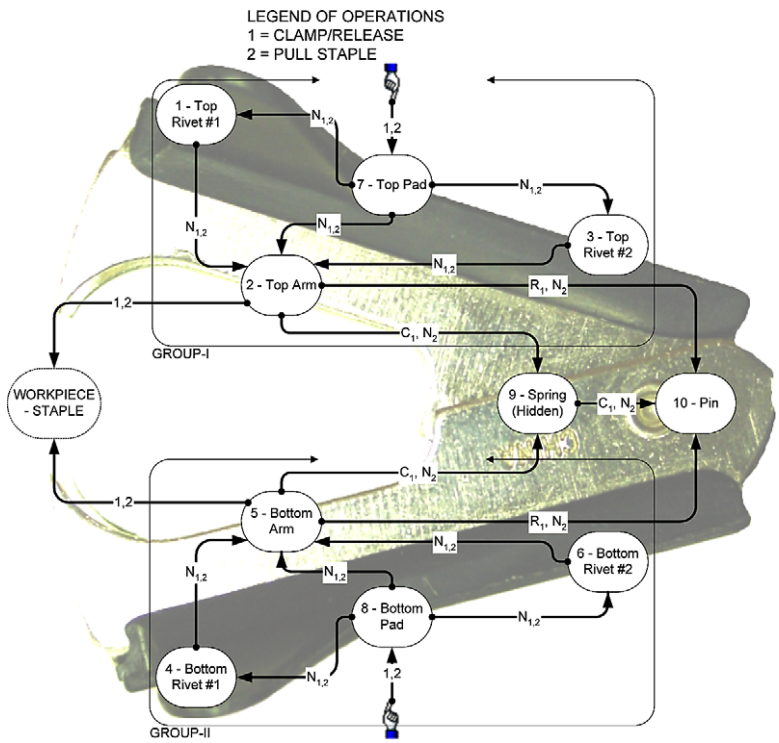

Figure 7 Effort flow diagram for the staple remover product

In terms of our extensions to effort flow analysis, the C-Links between the spring and its now combined neighbors lead to the application of the C-Link guideline to the C Group of Figure 8a. The result is the combination of one of the arms with the spring to produce three components as shown in Figure 8b. Which arm is selected is immaterial due to the symmetry

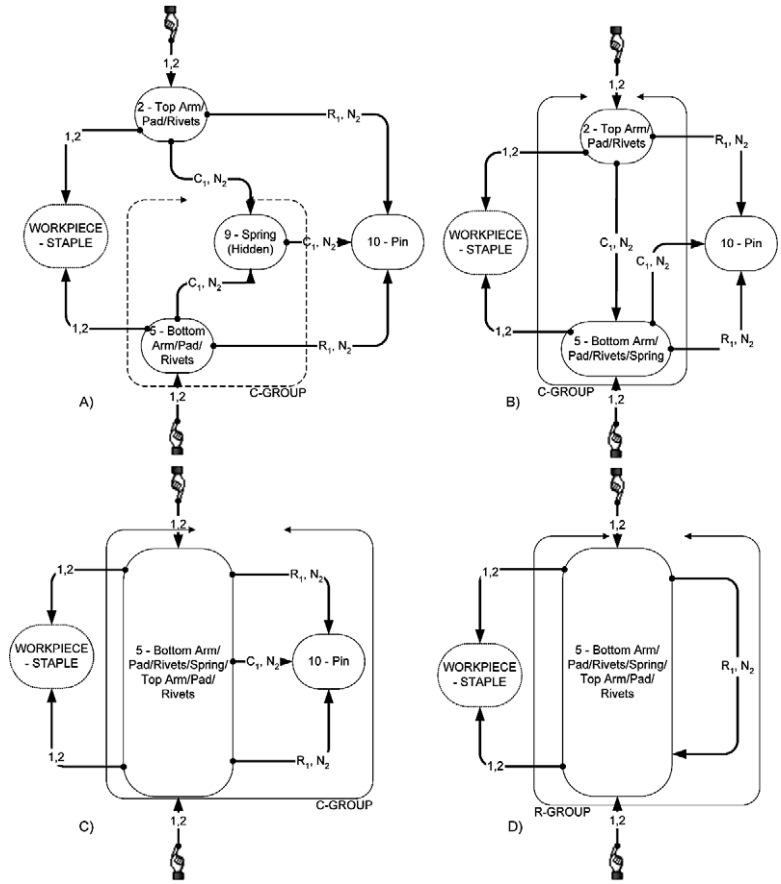

Figure 8 Guideline application sequence A–D

of the product. Continued application of the C-Link guideline pushes the evolution of the product (Figure 8a–c) to a point where only an R-Link exists between the component and itself. This seems absurd at first, but a moment of reflection will result in one if not several concept variants for a monolithic product having relative motion at one interface with itself. The next step in the process is to apply the R-link guideline, the result of which is the monolithic product modeled in Figure 9 and pictured in Figure 10. At this point, one must evaluate the results against the desired outcome.

Does the product satisfy the three solid mechanics criteria? No, it does not. Assuming the geometry is not changed, and a material is chosen, a conflict arises. An elastomeric material is compliant enough to achieve the deflection required but is too soft to satisfy the force transmission relationship at the interface with the staple (i.e. it does not possess sufficient hardness). A metal is strong enough to remove staples, but it is too stiff to be easily operated with the original geometry. For the device to be

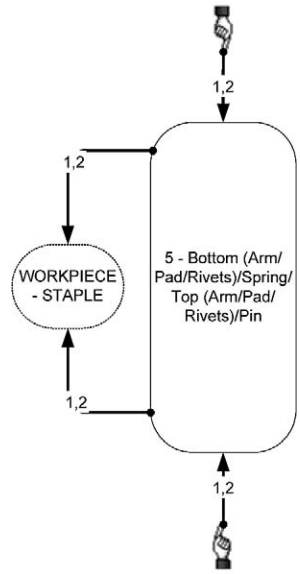

Figure 9 Effort flow diagram for one piece stapler

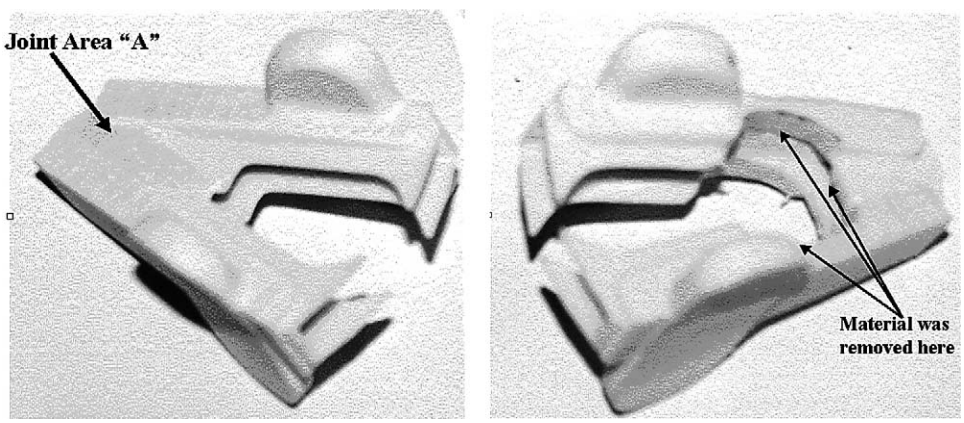

Figure 10 Single-piece staple remover

completely functional as a single piece, a blended material would be required. In a blended part, the hardness is attained at the tip of the claw while the required elasticity remains in the 'joint' area, a multiple material graded system using solid freeform fabrication processes might be another possibility.[35] In any case, there exists a conflict between two of the functional criteria.

To resolve this conflict, a step backward is taken, and a solution is achieved by separating the region of the product that must possess hardness (the tip) from the region that must be compliant (joint area A). To study this option,

35 Jepson, L J, Beaman, D, Bourell, B, Jackson, D, McAdams, J, Perez, J and Wood, K 'Multi-Material Selective Laser Sintering: Empirical Studies and Hardware Development' in Proceedings of the 2000 NSF Design and Manufacturing Grantees Conference, Vancouver, Canada (2000)

Figure 11 Five-piece staple remover with steel claws

a new staple remover with the original geometry is manufactured using a rapid prototyping technique (e.g. selective laser sintering). The required movement is very difficult to attain without rupture of the material, as the stresses are quite large in 'Joint Area A' of Figure 10a.

In order to reduce the high stresses, parametric changes in geometry are made. These parametric variations, shown in Figure 10b, involve decreasing the quantity of material in the joint area, thus allowing the device to maintain the needed movement of the claws while the stresses remain in the elastic region. To achieve the hardness in the claw area, metal jaws are inserted into the compliant polymer body as shown in Figure 11. This option increases the part count from one to five (body, 2-claws, 2-adhesives between claw and body), representing in a 50% reduction in number of parts from the original 10-piece system.

3 *Summary and future pursuits*

The purpose of this work is two-fold: (1) to review earlier work on effort flow analysis,[6,26–29] and (2) to show how effort flow analysis may be systematically applied for directed product evolution using part combination at interfaces where parts experience relative motion. As effort flow analysis evolves, novel approaches become apparent for product redesign. In this work, effort flow diagrams are extended to include a relative motion basis that includes four types of relative motion links, N, C, R, and I Links. The combination of parts connected via N-Links, C-Links, and R-Links are discussed in the context of both rigid and compliant mechanisms. Finally, the inherent difficulty associated with part combinations is highlighted across three classes of relative motion links. Examples of combin-

ing parts are given for two current products, a Quick Grip™ Clamp and a staple remover.

Future directions for this work include the development of a systematic methodology that allows the designer to begin with one of two design goals, evolution of the product, or revolution of the product. The path in the methodology is set depending on the stated goal. In addition, a systematic approach for dealing with the conflicts that result when components are combined across different material domains is under consideration. Finally, a method of identifying structures in the semantic network of the effort flow diagram that will lead directly to morphologies of the solution is under development.

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