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GUIDELINES FOR PRODUCT EVOLUTION USING EFFORT FLOW ANALYSIS: RESULTS OF AN EMPIRICAL STUDY

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ABSTRACT

The results of an empirical product study aimed at deducing product evolution design guidelines are presented. The derived design guidelines support a directed product evolution methodology known as effort flow analysis. Effort flow analysis provides a systematic framework for identifying component combination opportunities leading to either rigid-body or compliant mechanisms in the domain of mechanical effort transmissions. Design guidelines, effort flow analysis, and the empirical study are discussed. A classified list of the derived guidelines is presented along with analysis of a sample product group from the study.

INTRODUCTION

Effort flow analysis is a design methodology that leads to the directed evolution of products through the application of design guidelines that promote component combination. Component combination opportunities are identified by modeling products using an effort flow diagram. An effort flow diagram is a type of semantic network that maps the flow of effort (force or torque) as it transits through a product. Solutions to the identified component combination problems focus on melding or “morphing” geometry, with novel opportunities in compliant mechanisms. The focus of this paper is to introduce a set of product evolution design guidelines for use in effort flow analysis. These guidelines are derived from an empirical product study carried out as part of an ongoing research effort.

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BACKGROUND

The fundamental goal of product development is to create a product that satisfies the needs of a customer. The drive to continue satisfying customer needs leads to efforts toward product improvement. This improvement process is a part of the life cycle of the product. The Theory of Inventive Problem Solving (TIPS) suggests that the product life cycle consists of birth, growth, maturity, and decline, or more simply, evolution [1]. Effort flow analysis is a methodology aimed squarely at the task of directed product evolution in the birth, growth, and maturity phases of this life cycle. Though not strictly equivalent, product evolution may be thought of as analogous to Darwin’s theory of Natural Selection.

The crux of Darwin’s theory is that survival in the struggle for existence depends on the hereditary constitution of the surviving individuals leading to a gradual change in a population with favorable characteristics accumulating over generations [2]. Darwin’s theory provides a familiar frame of reference for the treatment of engineered products. In engineered products, evolution equates to the favorable features and functions of a product being maintained and propagated, while the undesirable traits are diminished. Hence, classes of products tend to evolve toward higher and higher levels of desirable features, while exhibiting a reduced number of undesirable traits.

Market place factors, such as changing customer needs and expectations, shareholder expectations, competitive pressures, and the overall economic climate, provide the motivation for product evolution. One of the key elements in keeping a product viable is identification of the desirable and undesirable features in both the product and the product’s of competitors. In general, this task is accomplished by understanding the needs of the customers and understanding the technical aspects of providing the product. Engineering design methodologies are a key tool in accomplishing these two critical tasks.

Design methodologies are an integral part of the broad-based management strategies used to increase the stakeholder value of an enterprise [4]. In the product design environment, a directed action approach to design is most appropriate rather than an *entirely* undirected exploratory approach that is often used in research. Analogous to the directed action and exploratory approaches are the two general classes of design methodologies presented in the literature: prescriptive and descriptive. These two classes of methodologies can be used for general problems in product design [1, 5, 6, 7, 8, 9, 10, 11, 12], or in product redesign [13, 14]. Integral to each of these methodologies is some level of design guideline used to support the capture and retention of design knowledge.

Design guidelines provide a means to store and reuse design knowledge with the potential to be effective in the early stages of design where shallow and broad knowledge is beneficial [15]. According to Roozenburg and Eekels [16], design rules can be either algorithmic or heuristic. Algorithmic rules are based on knowledge where the relationship between cause and effect is known well, as in physical laws, and they produce predictable and reliable results. Heuristic rules are based on weak knowledge where the relationship between cause and effect is less well defined and they are not guaranteed to result in the desired solution but are successful often enough to be useful. "Any design rule that cannot be converted into an algorithm is heuristic" [16]. The design guidelines presented here are based on observation of existing products, hence each has at least one successful implementation, but global success is not guaranteed. Based on this fact, the guidelines of this paper are heuristic in nature because they have been successful enough to warrant their application.

The capture of design knowledge is fraught with inconsistency. The inconsistency is due in part to variations in the terminology used to describe the various levels of captured design knowledge. For example, different authors use different terms to describe similar types of design knowledge; Suh [12] speaks of axioms as fundamental truths, while Edwards [17] uses the term Principle to describe the same level of knowledge. In light of this inconsistency, Nowack [15] proposes a general definition for a design guideline: "A prescriptive recommendation for a context sensitive course of action to address a design issue." According to Nowack, a design guideline has at least four parts:

issue(s) addressed or impacted,
links to design context,
action recommendations, and
rationale.

In this paper, the issues addressed or impacted by the guidelines are limited to those that affect the directed evolution of mechanical effort transmissions. The guidelines recommend actions to carry out effective product evolution through part combination or removal; the basis for these guidelines is in the observed design history of existing products. The individual guidelines of effort flow analysis provide the specific action recommendations and rationale.

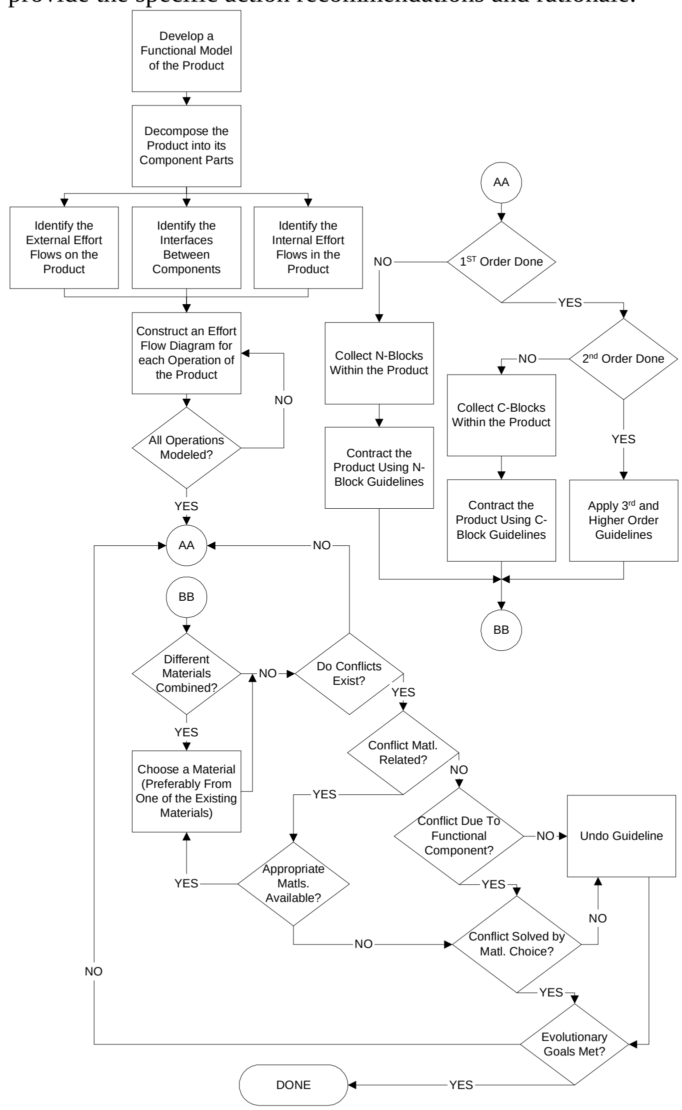


Figure 1: Effort flow analysis process flow

EFFORT FLOW ANALYSIS METHODOLOGY

Effort flow analysis is a systematic method for facilitating directed product evolution. Product evolution is accomplished by seeking component combination opportunities using both rigid body and compliant mechanisms. The products of interest come from the domain of mechanical effort transmissions. In this work, the term mechanical effort transmission is defined to be any device that transmits mechanical force or torque. Effort flow analysis is the evolution of a technique originally known as force flow analysis [13, 19-21]. In this work, the term *effort flow* will replace the original term, *force flow*. Effort flow analysis uses an effort flow diagram to model the transfer of effort (force or torque) through the components of a product. The effort flow diagram is a semantic network composed of nodes and links that are described using the fundamentals of graph theory [23, 24]. The nodes 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 they mimic the general topology of the product. An effort flow diagram maps the flow of effort from the input interface(s), through all the affected components, then to the output interface(s) for each operation.

An example effort flow diagram is presented in Figure 2 for a kitchen clip product used to hold closed previously opened bags (potato chips, etc.). Three operations are modeled in the effort flow diagram, which is superimposed over a photograph of the product. Look at *operation 1* (denoted by subscripts and link numbering) in the diagram. Follow the directed arrows from the human effort input by the upper hand. This effort is distributed through ARM #1 to: the interface between ARM #1 and the SPRING, and to the interface between ARM #1 and ARM #2. From these two interfaces, the effort is transmitted ultimately to the lower hand as a reaction to the input effort. The choice of which human interface is the input and which is the output is arbitrary; the direction of the flows follows from the choice. Modeling of the other operations follows similar logic.

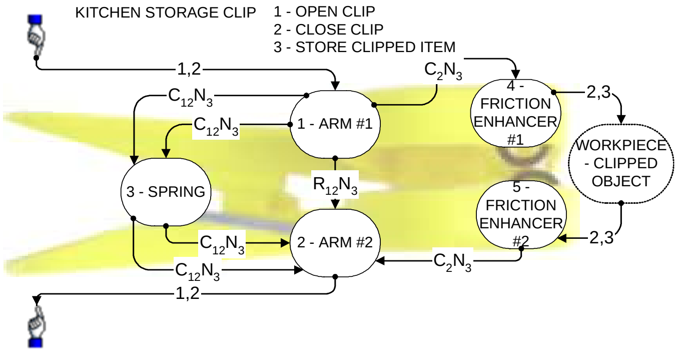


Figure 2: Effort Flow Diagram for a Kitchen Storage Clip

From this introduction, it should be clear that interfaces are a critical element in effort flow analysis. In this work, an interface is defined as:

> *A spatial region where energy and/or material flow exists between components or between a component and the external environment* [25].

This definition of an interface does not include the spatial or structural aspects that have been included by other researchers. In effort flow analysis, the focus is on the energy flow, one of the triad of fundamental functional flows: material, energy, and information. While a complete description of an interface is important in general design analysis, it is not necessary nor is it warranted to meet the goal of effort flow analysis, which is to describe as simply as possible the existence and fundamental characteristics of an interface.

The fundamental information needed to carry out effort flow analysis on a product is captured in the interface description contained in the links and their labels. This information set includes, at a minimum, the type of relative motion, the direction of the effort flow, and the operation with which the effort is associated. The interfaces are characterized based on the type of relative motion that exists between the connected components. Table 1 captures the permutations of possible relative motion types as well as the naming convention adopted to describe each possibility. Because this set spans all possible combinations of relative motion in mechanical effort transmissions, and because the members of this set are orthogonal, we will refer to the set as a *basis for relative motion* in effort flow analysis.

Four flow links are now possible. We define these links as follows:

- "N-Link": No relative motion either at the interface or between the components.
- "C-Link": Relative motion between the extents of the components but not at the interface.
- "R-Link": Relative motion both at the interface and between the components.
- "I-Link": Relative motion at the interface only.

Table 1: Table of Relative Motion Permutations

	Relative Motion Location	
Link Type	Between Interfaces	Between Components
N-Link	0	0
C-Link	0	1
R-Link	1	1
I-Link	1	0

Looking at Figure 2, the first three link types are present. The R-Link and N-Link are evident at the interface between the arms, and the C-Links at the interfaces between the arms and the spring and the friction pads. The fourth link type, the I-Link, is not evident in any of the product groups studied thus far, but extension of the methodology to other energy domains may produce examples.

The overall effort flow analysis process is graphically represented by the flow chart shown in Figure 1. The process begins with functional modeling and proceeds to modeling the product as an effort flow diagram. Once the product is modeled in an effort flow diagram, potential component combination opportunities can be identified. These opportunities become apparent during characterization of the relative motion at the interfaces between components [22]. These interface characterizations coupled with the structure of the graph lead the designer to apply particular design evolution guidelines. An example of the utility of the method, can be found by looking at the C-Links between ARM's #1 & #2 and the SPRING of Figure 2. These interfaces would be highlighted (a box drawn around it) and evaluated for possible combination using one or more of the design guidelines. The result of combining these components is a compliant mechanism leading to a part count reduction from five to three components. The design guidelines used in effort flow analysis result from an empirical study carried out on a set of existing products. The guidelines are classified as 1st, 2nd, and

3rd order or higher. These classifications indicate the expected likelihood of achieving a successful component combination with the particular guideline. In general, the classification follows from the links with which each is associated: N-Link – 1st order, C-Link – 2nd order, R-Links and others – 3rd order and higher.

EMPIRICAL STUDY

The purpose of this study is to develop product evolution design guidelines. These design guidelines are based on the observed evolution of products that capitalize on compliant mechanisms and other part combination opportunities in their design. The result is a set of product evolution design guidelines that are integral to the effort flow analysis methodology. The design guidelines provide the methodology with specific direction in the systematic generation of component combination concepts, such as compliant mechanisms, in product design and redesign.

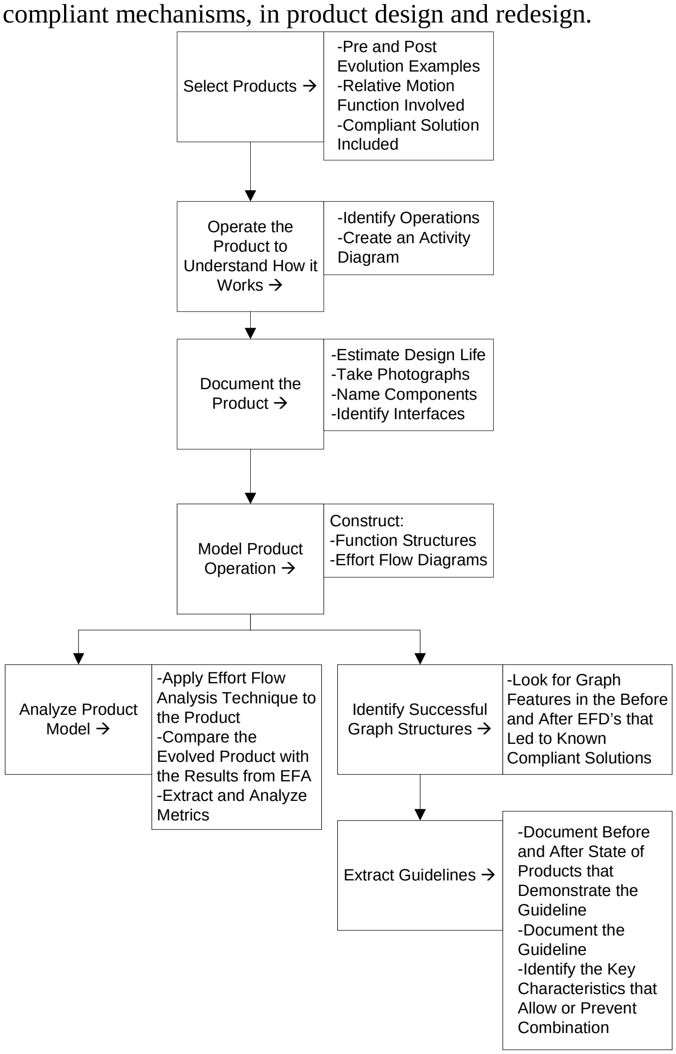


Figure 3: Empirical study process

Consumer products are selected as the data set for the study because they represent a significant aspect of design focus in industry [28]. In addition, these items are readily available for study. In order to establish a clear path of evolution in the study, each product group in the data set is chosen such that there exists a baseline product that does not exhibit significant component combination or use of compliance in its construction. This baseline product is used as the original design, and all other products in the group are compared to the baseline.

A block diagram representation of the procedure used in the study is shown in Figure 3. To read the diagram, follow the arrows downward in the direction of the flow; the main process steps are contained in those boxes attached to the arrows. The boxes attached to the main steps contain more detailed process information. It is interesting to note that effort flow analysis is being used within the loop of the study as a means to further its own evolution. In essence, effort flow analysis is a *living* method capable of furthering its own capabilities through the capture of design knowledge. Although the scope of the study is limited to products in the domain of mechanical effort transmissions, the ability of effort flow analysis to evolve through guideline collection may lead to its extension to other energy domains.

Guideline collection is carried out by modeling the baseline and evolved products using effort flow diagrams, and then determining the types of diagram contractions necessary to achieve the evolved product. Physically, a diagram contraction represents the combination of components, but manifests itself as a contraction of the graph in an effort flow diagram. The resulting hypothesized guidelines are based on observations of both the physical product and the abstract representation of the product contained in the effort flow diagram. In this way, the manipulation of the effort flow diagram can be related to the physical artifact it represents and the guidelines can be presented so they relate physical embodiments to specific arrangements of the links and nodes that repeatedly arise in the graph structure of the diagrams.

To demonstrate the approach taken in the study, a brief example of the overall process will be given for the kitchen storage clip product shown in Figure 4. Product selection is based on the existence of the baseline product and the evolved products. Operation of the product results in the activity diagram of Figure 5. The activity diagram leads to the operations, which are the user activities that will be modeled in the effort flow analysis. Once the customer needs and the associated operations are understood, the product is documented to include the component names, interfaces and pictures. Modeling begins with a functional model like the one shown in Figure 6, and then the effort flow diagrams for the product are developed (Figure 7). From these effort flow diagrams, the analysis, identification, and extraction steps are carried out. These three steps are the part of the study process where the guidelines are extracted from the model of the product.

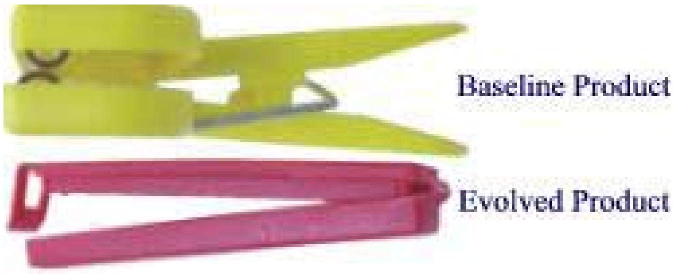


Figure 4: Baseline and Evolved Kitchen Clip Products

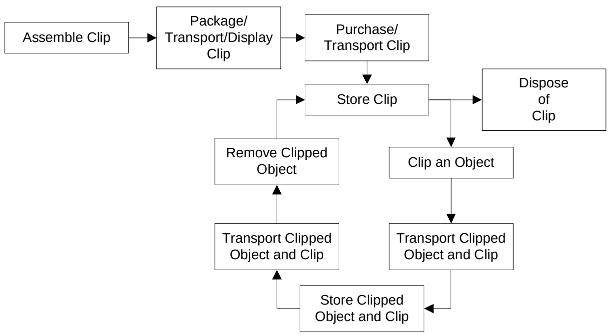


Figure 5: Kitchen Clip Activity Diagram

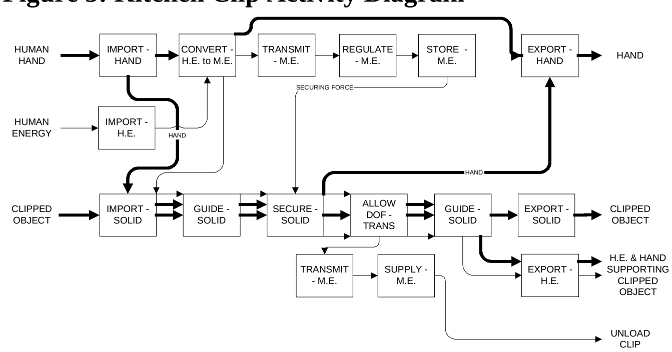


Figure 6: Kitchen Clip Function Structure

Analysis of Figure 7 leads to several hypothesis about product evolution guidelines. The first of those hypotheses comes from operation three. It is hypothesized that when a product performs multiple operations, if one of those operations produces only N-Links, then the associated N-Links can be disregarded on all links where more than one operation is active. The rationale behind this hypothesis is that although N-Links alone are opportunities for component combination, when they are coincident with other link types, the other relative motion type dictates the conditions for component combination.

Another guideline hypothesis is that integral attachment accompanied by strain energy can be used to replace the energy storage of the spring. The source of this guideline is the solution used to achieve the functional requirement to intermittently secure the clipped object. In the baseline product, this is achieved by stored energy in the spring acting against the interface between the arms and against the clipped object. In the evolved product, securing the clipped object is achieved by stored strain energy in the deformed beams acting against the hinge and integral latch to clamp the object between the beams.

Additional design guidelines from this product group and all the other product groups studied are contained in the guidelines of the next section. Following the guidelines section is a more comprehensive example of a product group from this study.

Validation of the guideline collection method is based on two premises. First, the design guidelines are deduced from observation of physical phenomenon in the baseline and evolved products. When these guidelines are applied to the baseline products from the product groups for which they were deduced, they produce the evolved product, hence they are at least valid for that product group. Second, all the guidelines reported here are verified by observation in studies of multiple product groups. In fact, several of the guidelines are observed in nearly all the product groups studied. While not completely rigorous, the validity of the study results is sound and reasonable in light of the definition for heuristic design rules discussed earlier. With the validity question answered, the design guidelines themselves can now be addressed.

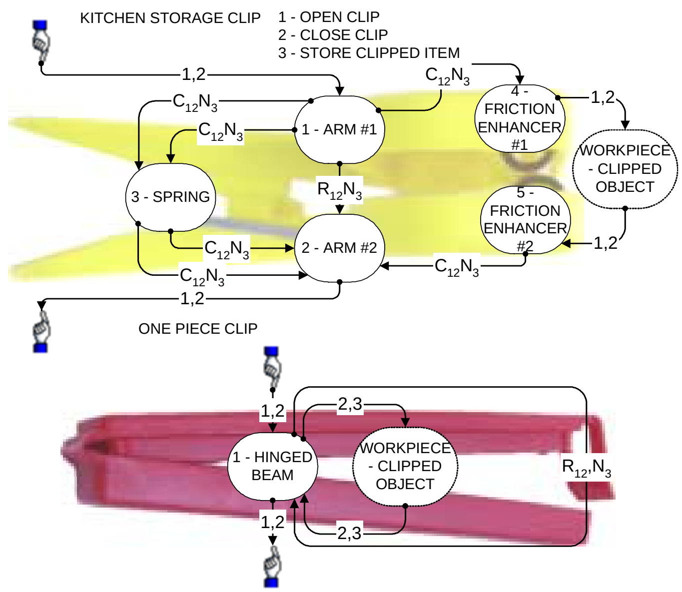


Figure 7: Effort Flow Diagrams for the Kitchen Clip Product

GUIDELINES

The format used to present the product evolution design guidelines is the *imperative form* from English grammar. The imperative form is used to construct verb phrases that make requests, give directions or instructions, or give orders or commands, where the context here is to give directions or instructions. This format is consistent with the *action-centered guideline model* used by Nowack, [15] where a design cycle operates from an initial *issue*, which motivates an *action* that produces a *consequence*, which in turn must be evaluated to see if it satisfies the original *issue*. In this model, guidelines embody the *action* that is taken to address the *issue*.

The result of guideline application, or *action*, is the *consequence*.

In order for this set of design guidelines to be useful, a classification scheme must be devised to aid the designer in finding those guidelines that apply to the design problem at hand. One approach to classifying design rules relating to compliant mechanisms is given in the work by Berglund *et al* [26], where the design rules for compliant mechanisms are classified using the following broad categories:

- Stiffness and Strength
- Material Selection
- Forces, Loads and Motion
- Geometry
- Manufacturing Issues

The difference between the *design rules* of Berglund and the *design guidelines* presented here is the level of specificity. The design rules are broad in scope covering general compliant mechanism design, while the design guidelines here work with components and interfaces at the product architecture level. This difference dictates that we take a different approach to classifying the guidelines. Here, the guidelines are sorted in such a way that they relate to the specific graph structures observed in the effort flow diagram.

The classification scheme proposed here is to use four broad classes to categorize the derived guidelines:

- <u>Relative Motion Domain</u>
    - *N-Link*
    - *C-Link*
    - *R-Link*
- <u>Graph Structure Domain</u>
    - *Parallel*
    - *Serial*
    - *Mixed*
- <u>Function Domain</u>
- <u>Analysis Domain</u>

The relative motion domain refers to the type of interface addressed in the guideline. The interface types are the NCIR interfaces discussed previously. The graph structure domain refers to the arrangement of the links (N, C, R, I) and nodes in the effort flow diagram; this domain is analogous to the arrangement, for example, of resistors in an electric circuit. Resistors can be in parallel, in series, or a mix of series and parallel elements. The graph structure domain treats these types of element arrangements. The function domain contains design guidelines that are related to the functionality of the combined components. Finally, the analysis domain contains design guidelines that are germane to the analysis of combined components in both rigid body and compliant mechanisms.

A summary of the design guidelines collected in the study is now presented in Table 2 through Table 5 using the domains suggested above. Several of the guidelines in the tables are referenced; these guidelines are gleaned from the literature for their applicability and are not the result of the empirical study.

Implicit in the following guidelines is the assumption that fundamental physical laws such as the strain/displacement law, the material constitutive law, and equilibrium conditions must be satisfied. In addition, any redesigned carried out using these guidelines must continue to satisfy the original product functions. These statements are embodied in the process flow chart of Figure 1, where any change to the model requires that the conditions for successful combination be satisfied.

Though each of the guidelines presented here may stand on its own merits, the real value lies in its application within the framework of the effort flow analysis process.

Table 2: Relative Motion Domain Design Guidelines

N-Links – 1st Order	
1.	Groups of components connected by N-Links are candidates for combination to rigid body structures. Combination is contingent upon the following constraints: a. Material strength/maximum stress is within acceptable limits b. Fatigue strength is at an appropriate level for the expected number of loading cycles c. Assembly/disassembly design features are not compromised [35] d. Original product functions continue to be provided Maintenance of the original material is desirable, however, material changes are allowed subject to the above constraints [35].
2.	When only N-Links are produced by one operation in a multi-operation model, the N-Links that are coincident with other link types can be omitted from the model, as the other link types will dictate combinability.

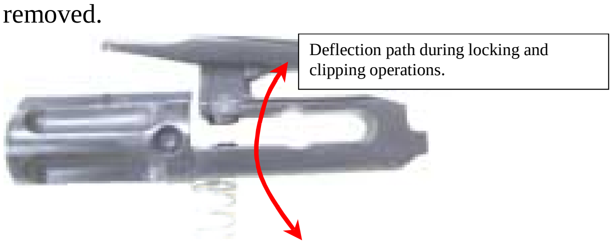
Table 2: Relative Motion Domain Design Guidelines continued	
C-Links – 2nd Order	
3.	Groups of components connected by C-Links are candidates for combination into compliant mechanisms. Combination is contingent upon following constraints: a. The DOF for the resulting interfaces with uncombined components are maintained b. Material strength/maximum stress is within acceptable limits c. Fatigue strength is at an appropriate level for the expected number of loading cycles d. Relationship between force and deflection is within acceptable limits where appropriate e. Assembly/disassembly design features are not compromised f. Original product functions continue to be provided Maintenance of the original material is desirable, however, changes are allowed subject to the above constraints.
4.	If combination across a C-Link requires relative motion be confined to a small region, use Localized or Lumped compliance solutions. Analysis of localized compliance is best suited to the pseudo rigid-body model method [36].
5.	If combination across a C-Link dictates that broad regions of a device be compliant, use Distributed compliance solutions. Analysis of distributed compliance requires the use of continuum models [37].
6.	When a C-Link enables a strain energy storage function, the components connected by the C-Link may be combined if the desired strain energy storage can be maintained using a compliant mechanism while still meeting other product functions..
7.	Compliant mechanisms made of polymer materials may need to be augmented by support structures to overcome the effects of creep when subjected to sustained loads. For example, the compliant mechanism in Figure 8 is augmented by a metallic coil spring. The purpose of the spring is deduced to be creep prevention, as the device performs all operations when the spring is removed.  **Figure 8: Pilot Pen clip/cap/index and spring components**
R-Links – 3rd Order or Higher	
8.	Components connected by R-Links, where the general relative motion is *small*, can be combined. In this context, small can be determined by the fatigue strength of the material at the point of maximum stress. Combination is contingent upon the following constraints: a. Deflection between the combined components is maintained with the combination, as defined by the R-link, with deflection requirements applicable at both the component interface and between the components. Deflection based design requirements must also be satisfied. b. Material strength/maximum stress is within acceptable limits c. Fatigue strength is at an appropriate level for the expected number of loading cycles d. Relationship between force and deflection is within acceptable limits where appropriate both at the component interface and between the components. e. Assembly/disassembly design features are not compromised with respect to interfacing components f. Original product functions continue to be provided Maintenance of the original material is desirable, however, material changes are allowed subject to the above constraints
9.	When one R-Link provides relative motion for two operations, the components connected by that link may be combined provided the motions are of the same type (translation or rotation) for both operations.
10.	R-Links where the motion is large (up to 359°) and the energy storage in the joint is to be minimized may be contracted if the effort transmission is small (only enough to generate motion) using localized compliance (a living hinge or similar type connection). The living hinge is especially useful in 2D motion.

Table 3: Graph Structure Domain Design Guidelines

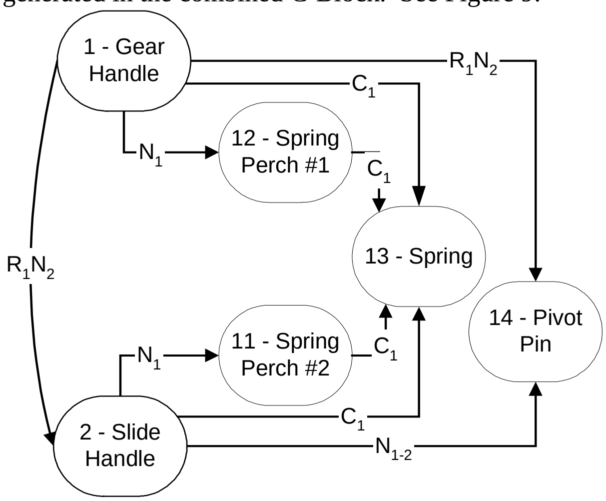
Series – 3^{rd} Order or Higher	
11.	When R-links of the same type (translation or rotation) are in series, then those connected components can be combined until an interface is reached where the required R-Link motions are of another type.
Parallel – 3^{rd} Order or Higher	
12.	When a block of components connected by C-Links contains C-Links that are in parallel with R-Links, the components connected by the C-Links may be combined if the relative motion at the R-Links can be maintained through the motion generated in the combined C-Block. See Figure 9.  **Figure 9: Graph Structure for Parallel R & C Links**
13.	Components connected by parallel links, which are determined to be functionally identical, are considered **redundant** and as a result can be reduced to a single non-redundant link. For example, two identical hinges result in 2 identical parallel link structures. By contracting the two links into one, no capability is lost, and complexity of the diagram is reduced. This guideline applies to links of any type.
14.	Components connected by **non-redundant** parallel links are candidates for component combination contingent upon the union of the constraints dictated by the guideline requirements for each specific link configuration.
15.	R-Links in parallel with energy storage C-Links are combinable using compliant components as long as the required strength, energy storage, and DOF can be maintained in the contracted compliant component.
Combined R & C – 3^{rd} Order or Higher	
16.	When an interface consists of an R-Link and a C-Link, the two relative motions must act in different or orthogonal degrees-of-freedom.
Combined R & N – 3^{rd} Order or Higher	
17.	Components connected by RN-Links (i.e. links which are designated as R-links for one or more operations and N-links for one or more different operations) are candidates for combination. Combination is contingent upon the constraints afforded by both the R and the N-link as follows: a. Deflection based functions are maintained with the combination, as defined by the R-link, with deflection requirements applicable at both the component interface and between the components. Design requirements must also be satisfied. b. Material strength/maximum stress is within acceptable limits c. Fatigue strength is at an appropriate level for the expected number of loading cycles d. Relationship between force and deflection is within acceptable limits where appropriate e. Assembly/disassembly design features are not compromised with respect to interfacing components f. Original product functions continue to be provided. Maintenance of the original material is desirable, however, material changes are allowed subject to the above constraints
18.	R-Links and N-Links that occur on the same link for different operations are combinable using a **rigid body** if the DOF can be moved up or down the flow path from the link of interest.
19.	R-Links and N-Links that occur on the same link for different operations are combinable using **compliant mechanism** when the required DOF can be maintained in the combined component.

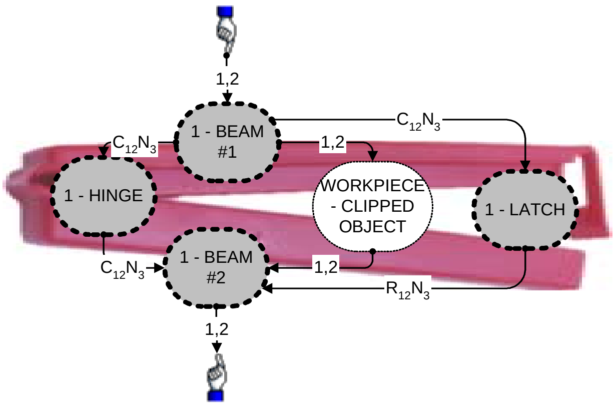
Table 3: Graph Structure Domain Design Guidelines (continued)	
Combined C & N – 3rd Order or Higher	
20.	C-Links and N-Links that are coincident on the same interface are combinable provided the required constraint on the DOF needed for the N-Link can be achieved using a compliant member. A link of this type appears to be a combination of the N-Block and C-Block contraction opportunities. This guideline stems from the kitchen clip product group discussed earlier, and is evidenced in the structure of Figure 7 where the arms and spring of the baseline product are combined to produce the beams, hinge and latch in the evolved product. In this case, the DOF constraint is changed from resisting a compressive load in the original product to resisting a tensile load in the evolved product. In addition, the constraint on out-of-plane motion enforced by the interface between the arms of the original product is enforced by the hinge and latch of the evolved product.  **Figure 10: Resulting monolithic structure shown as functional components in clip product** The product modeled in Figure 10 is a one-piece product, the separate nodes are used to show which portions of the product provide particular functional features.
21.	Components connected by CN-Links (i.e. links which are designated as C-links for one or more operations and N-links for one or more other operations) are candidates for combination. Combination is contingent upon the constraints afforded by both the C and the N-link as follows: a. Deflection between the combined components is maintained with the combination as defined by the C-link b. Material strength/maximum stress is within acceptable limits c. Fatigue strength is at an appropriate level for the expected number of loading cycles d. Relationship between force and deflection is within acceptable limits where appropriate e. Assembly/disassembly design features are not compromised with respect to interfacing components f. Original product functions continue to be provided. Maintenance of the original material is desirable, however, material changes are allowed subject to the above constraints.

Table 4: Function Domain Design Guidelines

22.	Integral attachment accompanied by strain energy (distributed compliance) can be used to replace the energy storage of a spring.
23.	The DOF afforded by an R-Link may not need to be a part of the product being modeled, the DOF may be transferred from the system of interest to the system of an interfacing external system such as the human interface, which is not part of the actual product.
24.	Living hinges can be used in high load applications when the loading is tensile only [36].
25.	When an EFD affords multiple choices for possible graph structure contractions (e.g. possibility for combining component A with either component B or component C), each possible solution path should be followed to it's maximum evolved state.

Table 5: Analysis Domain Design Guidelines

26.	When bending deflection is specified, reduce the second moment of area to reduce the stress and thus the likelihood of fatigue failure in a compliant mechanism. The mechanics behind this result follow the argument that a desired deflection is specified: $I = \frac{bh^3}{12}$ (1) $\delta = \frac{FL^3}{3EI}$ (2) The maximum or minimum force required to achieve that deflection is then specified, and equation 2 is solved for the force ***F*** as in equation 3. Equation 3 is then substituted into equation 4 for ***F*** resulting in a relationship for stress as a function of ***h*** for a given deflection as shown in equation 5. $F = \frac{3\delta EI}{L^3}$ (3) $\sigma = \frac{h}{2}\frac{FL}{I}$ (4) $\sigma = \frac{3h}{2}\frac{\delta E}{L^2}$ (5) Note that as ***h*** is reduced, the stress is reduced, as is the second moment of area, ***I***, hence to achieve a given deflection with a minimum tensile stress due to bending, the objective is to reduce ***I***. The most effectively way to do this is to reduce ***h***. This result is related to the guideline proposed by Berglund [26] where it is stated "Avoid adding material to a compliant segment if it experiences static or fatigue failure in bending." This guideline is confirmed in the second iteration of one of the study subjects, an evolved compliant ice cream scoop, where the thickness of the bending beam compliant segment is reduced in the evolved product; see Figure 11 for details.  **Figure 11: Example of reduced thickness in a bending beam**
27.	Materials with the highest strength-to-modulus ratio will allow a larger deflection before failure. This ratio is one of the most important factors in selecting a material for a compliant mechanism [36].
28.	In systems with both living hinges and other compliant segments, the rigidity of the living hinges is often so low compared to the other flexible components that their rigidity and energy storage can be ignored [36].
29.	When the resulting compliant design dictates that the relative motion is confined to a small region, then use Localized or Lumped compliance solutions, such as a living hinge. Analysis of this type of compliant mechanism is best suited to the pseudo rigid-body model method [36].

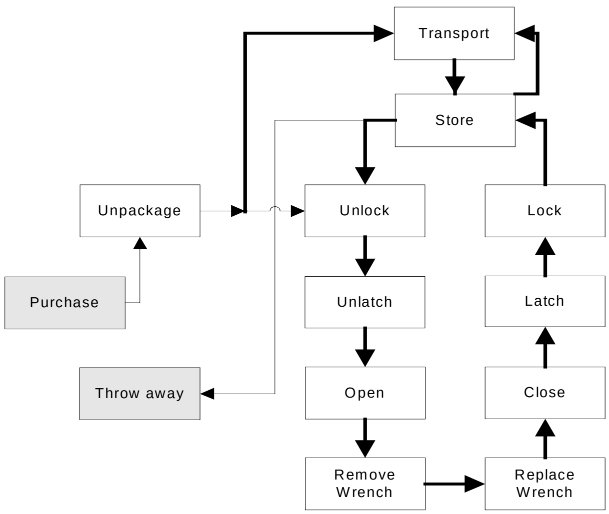


Figure 12: Tool Case Activity Diagram

GUIDELINE DEVELOPMENT EXAMPLE

An example will illustrate how effort flow analysis is used to derive the guidelines presented in this paper. A tool case product used to store and transport lightweight hand tools is used to demonstrate the methodology. The baseline product is constructed from a mix of 19 separate polymer and metallic components. The evolution of the baseline product is charted through three intermediate products to a fully evolved product. To understand the operations that need to be modeled for this product group, an activity diagram is constructed and is shown in Figure 12. These operations are the: Unlock, Unlatch, Open, Close, Latch, Lock, and Transport operations. A legend is included in the effort flow diagrams of Figure 13 where the subscripts on the link labels indicate the operation for which the link is active. The effort flow diagrams of Figure 13 are models of the baseline, intermediate, and the fully evolved products superimposed onto images of the actual products. The progression of the products in the figure starts from the baseline product in the top left and progresses in a clockwise manner until the fully evolved product is reached in the bottom left corner. Some of the guidelines hypothesized through analysis of the tool case product group are now presented.

All the products in this example are shown in Figure 13. Each product in the figure is numbered from 1-5, where product (1) is the baseline, and product (5) is fully evolved. Examples of two Relative Motion Domain guidelines (Table 2) are represented in the evolution of the baseline tool case.

1. Guideline 1, has four instances:
    a. Combination of the Rivets 6 & 7 and the Bracket into the Lid from product (1).
    b. Combination of the Hinge Pins and the Base from product (2).
    c. Combination of the Latch Pin and Latch Lever in going from product (2) to product (4).
    d. Combination of the Latch Hook with Rivets 4 & 5, and combination of the Latch Bracket with Rivets 6 & 7.
2. Guideline 2 has one instance: In product (4), operation 7 produces only N-Links and can hence be neglected for effort flow analysis of this product.
3. Guideline 10 has one instance: Combination of the Latch Ring and Latch Lever is possible by moving the relative motion between these two parts to another interface resulting in the combined Latch Lever and Ring of Product (4)

Two Graph Structure Domain guidelines (Table 3) are especially prevalent in the evolution of this product group.

1. Guideline 17 has three instances:
    a. Combination of the Latch Lever, Latch Ring, and Latch Pin from either product (1) or (2) results in the compliant Latch Ring of product (3).
    b. Combination of the Lid and Base from either product (3) or (4) results in product (5).
    c. Combination of the Latch Ring and the Lid of product (4) leads to the integral latch mechanism of product (5)
2. Guideline 20 has three instances:
    a. The combined Latch Hook and Rivets 4 & 5 discussed previously are subsequently combined with the Lid for all products subsequent to the baseline product.
    b. The combined Latch Bracket and Rivets 2 & 3 discussed previously are subsequently combined with the Base for all products subsequent to the baseline product.
    c. Combination of the Latch Rings with the Lid of product (3) produces a one component lid and with integral latches in product (5).

In addition to the relative motion and graph structure guidelines, observations that are more general lead to guidelines in the Function Domain and the Analysis Domain.

1. The DOF afforded by an R-Link may not need to be a part of the product being modeled. This observation comes from the integration of the movable handle of products (1)-(3) into an integral handle in products (4) and (5). In this case, the DOF has been transferred to the human interface, which is not part of the actual product (Guideline 23).
2. Living hinges are appropriate when heavy loads are not involved (Guideline 24).
3. When an EFD affords multiple choices for possible graph structure contractions (e.g. possibility for combining component A with either component B or component C), each possible solution path should be followed to it's maximum evolved state. Comparisons among the solution paths and results can then be made and the solution that best satisfies the functional requirements is chosen (Guideline 25).

This discussion on hypothesized guidelines is a brief overview of the guidelines gathered from the tool case product group. This example shows the study process and highlights some of the results.

RESULTS AND DISCUSSION

To date, eight product groups consisting of approximately 23 separate products have been studied to produce the guidelines presented in this paper. The prevalence of these guidelines in demonstrated applications lends credence to their validity. In the example presented here, a small handful of principles are applied repeatedly resulting in a reduction in the number of parts from 19 to 1. It is claimed here that these fundamental guidelines are responsible for this dramatic product evolution, and that their application to other products should yield similar results.

The goal of this research effort is then to incorporate these guidelines into the overall effort flow analysis methodology. The methodology that results is a systematic methodology for the synthesis of designs that incorporate component combination and novel compliant mechanisms in the design and redesign of products from the domain of mechanical effort transmissions.

Future work includes the development of an interface between effort flow analysis and specific analysis tools such as the finite element analysis and the empirical similitude methods. The goal of this effort is to provide a comprehensive process that takes the original product as an input and produces a viable product design as the output.

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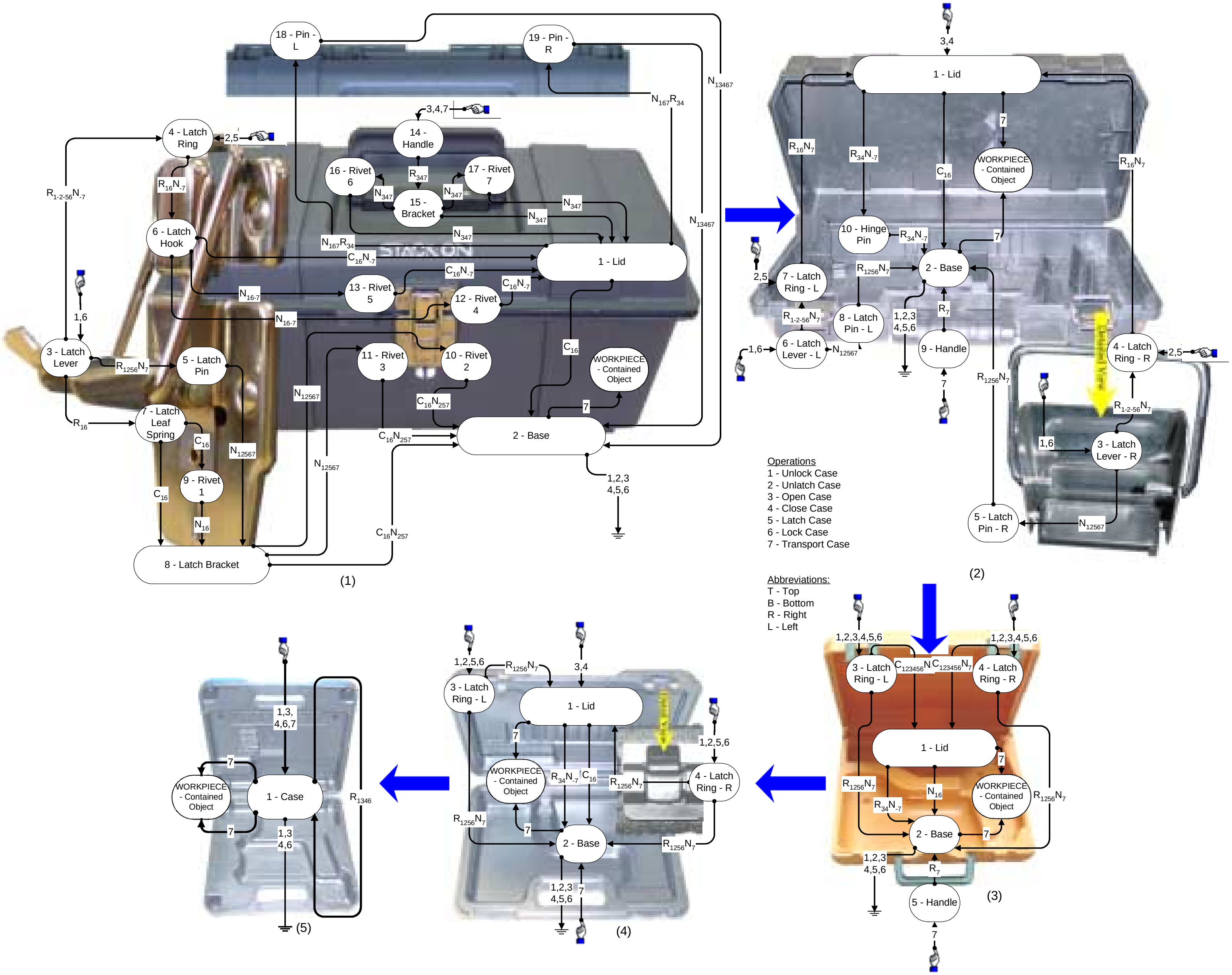

Figure 13: Effort Flow diagrams for Baseline and Evolved Tool Box Products.

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