Proceedings of the ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
IDETC/CIE 2008
August 3-6, 2008, Brooklyn, New York, USA

DETC2008-49891

TRANSFORMATION FACILITATORS: A QUANTITATIVE ANALYSIS OF RECONFIGURABLE PRODUCTS AND THEIR CHARACTERISTICS

Jason M. Weaver
jasonweaver@mail.utexas.edu

Kristin L. Wood
wood@mail.utexas.edu

Manufacturing and Design Research Laboratory
Department of Mechanical Engineering
The University of Texas
Austin, TX 78712-0292

Dan Jensen
Dan.jensen@usafa.af.mil

Department of Engineering Mechanics
United States Air Force Academy,
USAF Academy, CO 80840-6240

ABSTRACT

Products that transform into multiple states give access to greater flexibility and functionality in a single system. These "transformers" capture the imagination and can be elegant, compact, and convenient. Mechanical transformers are usually designed *ad hoc*; a methodology specifically aimed at creating transformation processes would help the designer better understand when to use transformation and how to best seize its advantages and avoid its pitfalls. There is an underlying common basis of principles and facilitators (e.g. *Fold*, *Share Core Structure*, *Segment*) that describes transformation processes. We conducted an empirical study of 190 reconfigurable products across several domains, observing the overall trends in how transformation occurs. We confirmed the consistent use of similar principles and facilitators across the design space, and we quantitatively determined the extent of correlation among them. This paper lays out characteristics and interactions that are popular in current transformer design, as well as opportunities for innovation in new directions. A case study is also presented that illustrates how these results can be used in the future to help develop a step-by-step methodology for generating concepts of transforming products.

KEYWORDS

Design Principles; Transformational Design; Design Transformation Theory; Empirical Study, Reconfigurable Products, Design Matrix Analysis

1. INTRODUCTION

The term "transformer" may bring to mind images of alien robots, but many realistic examples of transforming systems surround us. Reconfigurable products, such as furniture, vehicles, tools, and other gadgets can be designed to move between two or more functional states. Transformation design theory defines a transformer as *a system that changes state in order to facilitate a new functionality or enhance an existing functionality* [1]. For example, the product below has two configurations: a chair and a ladder (Fig. 1).

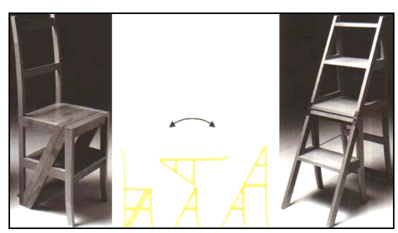

Figure 1. Transforming Chair/Ladder [2].

By cleverly including a folding action, the designer doubles the functionality of the product without compromising, in any significant way, the customer needs related to either function. Transforming, or reconfigurable, products can take less space and be more convenient than two separate products.

They can also be more flexible and elegant than a single-state product with the same functionality.

Transformers are currently used in a number of domains, ranging from simple multipurpose tools to expensive and complex military hardware. Well-designed transformers, such as the expanding table in Fig. 2, are simple, with user interfaces that hide any inner complexity of the transformation process. Each state should provide what the user needs at the time, without tacking on superfluous space, weight, or complexity. However, poorly designed transformers can easily become too complex, unwieldy, or confusing.

Figure 2. The Capstan expanding table conceals a complicated transformation process behind a user interface of simply rotating the table top [3].

Due to the possible pitfalls and complexity of transforming products, more care in the design process may be necessary than for an equivalent non-transforming product, resulting in possible higher costs. It is therefore critical to provide guidance in the process of efficiently generating transformer concepts, rather than leaving this step to *ad hoc* processes. A transformer design theory would help designers identify when transformation is useful, a large number of ideas available for transformation, how to best seize upon the possible advantages of multiple states, and how to avoid or minimize any disadvantages.

1.1 MOTIVATION

Currently, the design community does not have many tools specifically geared toward transformation. The complexity of intermeshing states with different customer needs, functions, and conflicts makes successful transformer design an intimidating goal. Much research has been done on specific areas of transformation, such as robotics and space exploration [4,5], as well as flexible manufacturing processes [6]. Individual designers and companies have identified trends and use domain-specific design processes [7,8]. However, comprehensive transformation design theory is still in its infancy. Several well-known design tools are sometimes used as launch points in the design process. For example, quality function deployment (QFD) identifies key engineering parameters and possible conflicts [9-11]. Theory of inventive problem solving (TIPS) helps find innovative solutions to those conflicts, which may or may not involve transformation [12]. Functional modeling can aid in noting modules that can be altered between states to facilitate transformation [13,14]. Design by Analogy draws examples of what works well from other products or systems [15-17]. Yet, despite their strengths, these methods do not focus significantly on the actual mechanics of transformation.

In the past, transformation processes were often designed *ad hoc*, starting from scratch for each new product. However, examination of transformers shows that many principles are common across the design space. Consciously or unconsciously, the design community follows certain guidelines that can mean the difference between a streamlined multi-state product and a confusing mess. If this wealth of experience can be tapped and formulized into a transformation design theory and methodology, designers can avoid reinventing the process and move forward, better understanding why transformers are designed the way they are, and how and when to take advantage of transformation.

1.2 OBJECTIVE

The objective of this paper is to examine the current design space of transformers using an empirical method and identify key trends and relationships shared across the compiled examples. These common trends can be analyzed to understand, first, why the trends in transformers exist, and second, how following or violating these trends can lead to new, innovative designs.

Previous work in transformational design has identified a set of principles and facilitators that enable transformation, as explained in the next section. This paper primarily focuses on discovering how these principles and facilitators relate to each other and how they can be used to best exploit the possibilities of transformation.

2. TRANSFORMATION PRINCIPLES AND FACILITATORS

Previous research compiled a list of three transformation principles and twenty transformation facilitators [1, 18-20]. It has been hypothesized that these principles and facilitators create a complete basis by which all mechanical transformation processes can be described.

2.1 PRINCIPLES

A transformation principle is “a generalized directive to bring about a certain type of mechanical transformation.” It describes what type of transformation takes place without specifying how it is accomplished. When embodied in a device, one principle can singly create a transformation. Principles are active verbs, with an expressed duality between the states of a system or product. The three principles are listed in Table 1, with definitions in Appendix A.

Table 1. Transformation principles.

1. Expand/Collapse
2. Expose/Cover
3. Fuse/Divide

2.2 FACILITATORS

A transformation facilitator is a specific means of movement or change that aids or facilitates the transformation process. They are implemented in conjunction with at least one principle, and often work together with other facilitators. Without an encompassing principle, a facilitator cannot singly create a transformation in a device. Facilitators, like principles, are worded as active verbs or verb/object pairs. As an illustration, refer to the transforming chair/ladder in Fig 1. It primarily uses the principle *Expose/Cover*, with the facilitators *Conform with Structural Interfaces*, *Flip*, *Fold*, *Segment*, and *Share Functions* working together to enable the principle. The 20 discovered facilitators are outlined in Table 2, with definitions found with the principles in Appendix A.

Table 2. Transformation Facilitators.

1. Conform with Structural Interfaces
2. Enclose
3. Fan
4. Flip
5. Fold
6. Furcate
7. Inflate
8. Interchange Working Organ
9. Modularize
10. Nest
11. Roll/Wrap/Coil
12. Segment
13. Share Core Structure
14. Share Functions
15. Share Power Transmission
16. Shell
17. Telescope
18. Utilize Composite
19. Utilize Flexible Material
20. Utilize Generic Connections

2.3 INDICATORS

Transformation principles and facilitators illustrate *how* transformers change states, but do not address the question of *when* to incorporate transformation into a design. Preliminary research [15-17] postulates three "indicators" that a design has potential for transformation. The following scenarios may benefit from transformation:

1. The system needs packaging for portability and deployment.
2. Multiple systems would be more convenient if consolidated into one system.
3. Multiple systems have dissimilar configurations, but share common material and/or energy flow.

The first indicator captures systems with such needs as a smaller or more protected storage state or a portable state. (for example, a compact satellite system that deploys after launch). The second indicator points towards systems that may be used at the same location or in closely related tasks, but at different points in time, such as an ice skate that transforms into an inline skate. The third indicator considers systems that are not closely related, but are actually functionally or physically similar, such as a cane transforming into a sword. It is not uncommon for multiple indicators to occur together. In general, transformation seems beneficial if a system must fulfill different functions at different times. If the different configurations are needed simultaneously, then transformation should not be pursued.

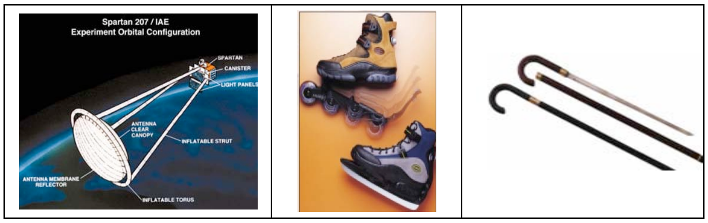

Figure 3. Examples of the three indicators: The IAE satellite deploys by inflating [21], inline and ice skate modules attach to a core boot structure [22], a cane conceals a blade [23].

3. RESEARCH QUESTIONS

The research and analysis presented in this paper seeks to answer the following questions:

- Does the current set of principles and facilitators form a complete basis for all transformers? Are the definitions robust and complete?
- What domains are transformer-rich?
- What principles and facilitators are the most dominant?
- Which often go together? Which don't?
- Are there interesting chains of facilitators? What are interesting exceptions?
- Can the three indicators of transformation-readiness be verified?
- How does this information help design better transformers?

4. RESEARCH METHOD: TRANSFORMER REPOSITORY

These questions are investigated through an empirical study of transforming systems. A repository of transformer examples was formed to gather enough data for trends to be established. This repository currently contains 190 distinct transformers, which when expanded out fully, represents over 400 instances of transformation principles at work.

4.1 RESEARCH METHOD

Many sources were used to identify these transformers. First, previous research in this area has yielded multiple papers containing a large number of example products [1,18-20]. Second, several books illustrate design principles used in applicable areas, particularly collapsible/deployable structures. One notable example is Mollerup's *Collapsible: The Genius of Space Saving* [2]. A third method is simple observation. Stores, magazines, television, and everyday activities yielded a multitude of commonly available transformers [24-26].

The Internet proved an invaluable resource as well. Several industrial-design websites list new products and concepts that the authors find novel, elegant, or otherwise noteworthy [27,28]. Many of these examples also utilize transformation. In addition, links and advertisements from these sites often led serendipitously to new examples and sources. Another method used to fill the repository is keyword searches. A systematic method of patent search using keywords to find transformers has been presented previously [19]. Some example keywords that were successfully used on patent websites such as www.freepatentsonline.com and www.uspto.gov include "expand furniture," "changes into," "multifunctional," and "transform toy." This approach was also used effectively with general Internet searches, such as www.google.com.

This multi-pronged method of filling the repository resulted in a list of transformers covering a wide range of backgrounds. Many different domains are represented, from military aircraft to consumer electronics to clothing. Size varies from small stents placed in arteries to enormous tennis stadiums [29,30]. Although no such list could be said to be complete and unbiased, the data gathered in this research is broad enough to demonstrate a very wide variety of the characteristics and trends common across the design space.

4.2 LAYOUT

After compiling the repository of transformers, we recorded each example in a spreadsheet with the following information:

- Source of transformer example
- Which principles and facilitators are exhibited
- Number of states
- Domain (vehicle, structure, storage, etc.)
- Method of discovery (patent search, etc.)

The spreadsheet was organized as a matrix, with transformers as rows and the above information as column entries. For example, each principle and facilitator was given a separate column, with an entry of 1 or 0 in each cell dependant on whether the given transformer exhibits the principle or facilitator. This allowed us to sort the list by characteristic and analyze the data using matrix operations.

5. ANALYSIS OF REPOSITORY

In analyzing the repository, we first considered the effectiveness of the current vocabulary in describing the chosen transformers. We found that all examples in the repository could be described by the current set of principles and facilitators. Biological transformers were sometimes awkward or strained in their description; for example, a tadpole that changes on a cellular level into a frog requires some muddying of the facilitators *Inflate*, *Utilize Composite*, *Utilize Flexible Material*, and others. Despite this murkiness at such high complexity, the current system was more than adequate to clearly describe what happens in transforming mechanical devices. As we delve further into non-mechanical areas, additional refinement of definitions may help simplify the classification process, but the current set of principles and facilitators appears to cover all mechanical transformers encountered thus far.

As stated previously, the repository contains examples across a broad range of domains. The transformers selected seemed to fall into the following general categories or domains:

- Organisms
- Structures (including buildings and furniture)
- Tools (including appliances, personal accessories, toys, weapons, etc.)
- Vehicles (cars, skates, wheeled robots, etc.)
- Storage (with no other function)

The 190 transformers encompass a total 428 states, consisting of 42 organisms, 107 structures, 147 tools, 86 vehicles, and 46 exclusive storage states. In addition, many of the non-storage "active" states incorporate storage as a secondary function. Over these general domains, the repository seems to be reasonably balanced in its scope, although it does have a bias toward tools due to both the breadth of the domain and the wider media exposure for "gadgets."

After this summary inspection of the repository, we sorted the list by domain and examined what principles and facilitators were primarily used. For each domain, the sum number of examples using each principle and facilitator was computed. Because of the different number of examples in each domain, these results were normalized to find the percentage of transformers in the domain that exhibit each principle or facilitator. These results are found in Table 3.

Overall, all domains demonstrate similar proportions of principle and facilitator use, with a few exceptions. Biological organisms tend to make more use of flexible material and less segmentation and structural interfaces to aid transformation than the other, man-made domains. Organisms also gravitate toward using a core structure shared between states. Structures make less use of shared power transmission than average, since most structures are static in nature. Conversely, vehicles demonstrated a higher than average tendency to share power transmission between states, as well as a high degree of modularity and shared core structure. Finally, exclusive storage states almost always incorporate the principle *Expand/Collapse* and are less likely to share a core structure

Table 3. Prevalence of principles and facilitators in each domain. Values 20% away from column averages are highlighted.

	Expand / Collapse	Expose / Cover	Fuse / Divide	Conform w/ Struct. Int.	Enclose	Fan	Flip	Fold	Furcate	Inflate	Interchange Working Organ	Modularize	Nest	Roll/Wrap/Coil	Segment	Share Core Structure	Share Functions	Share Power Transmission	Shell	Telescope	Utilize Composite	Utilize Flexible Material	Utilize Generic Connections
Percent of Organisms	68	73	36	50	27	32	59	45	14	23	9	55	55	32	50	77	73	27	59	18	32	82	18
Percent of Structures	67	84	40	95	22	33	64	56	13	4	4	60	73	15	91	44	71	4	85	25	42	22	15
Percent of Tools	66	75	37	92	34	26	58	53	14	7	14	62	68	18	77	40	75	32	78	23	27	33	25
Percent of Vehicles	57	76	48	91	26	30	59	67	9	9	28	91	63	24	85	80	76	48	67	11	20	26	30
Percent of Storage	93	87	22	93	37	35	59	67	11	11	4	46	80	28	74	24	59	9	89	22	50	39	15
Percent of All Products	65	77	39	88	27	31	59	56	13	8.4	14	67	67	21	79	55	73	28	75	19	31	34	23

20% more than average	(green)
20% less than average	(yellow)

than other domains. These outliers match what is observed commonly; the similarity otherwise among domains indicates that the relative prevalence of principles and facilitators in design is not primarily dependent on the domain of the product.

5.1 PRINCIPLE AND FACILITATOR MATRICES

We now turn to the principles and facilitators themselves. As seen above, there is a wide range in the prevalence of these characteristics over the design space. In the repository used for this paper, 164 out of 190 transformers used the facilitator *Conform with Structural Interfaces*, while only 14 made use of the facilitator *Inflate*. To gain more insight, we began by organizing the information into a square matrix we will call the PF matrix.

This form of analysis was inspired by a similar procedure used by Stone, Wood, and Crawford in their analysis of correlations between function structure and customer needs [10]. In their research, Stone et al. created a product repository matrix with products as columns and functions as rows. They multiplied this matrix by its transpose to create a symmetric matrix. This was done in two different ways. Pre-multiplying the matrix by its transpose (i.e. A^TA) resulted in a matrix with the original column entries (products) along both rows and columns. In this Product-Product matrix, the diagonal entries are the number of functions found in the given product, and the off-diagonals show how many functions are shared between the product in the row and the product in the column. Conversely, the matrix was also post-multiplied by its inverse (AA^T) to yield the symmetric Function-Function matrix. This matrix yields the number of times a given function occurs in the repository along the diagonal, and the off-diagonals show the number of products that include both the function in the row and the function in the column. Both of these matrices can be normalized in various ways to create a sort of similarity index that can be used to group similar products into families and commonly shared functions into groups and modules.

A similar approach was taken with the transformer repository in this paper. By pre-multiplying the entire repository matrix by its transpose (R^TR), a symmetric matrix is created with principles and then facilitators along both rows and columns. This can be analyzed as four independent sub-matrices: a Principle-Principle matrix, a Principle-Facilitator matrix, its transpose the Facilitator-Principle matrix, and the Facilitator-Facilitator matrix. Since the four matrices will typically be presented together in this paper, the entire matrix will be referred to simply as the PF matrix for brevity.

5.2 UNWEIGHTED PF MATRIX

The first iteration of the PF matrix is the multiplication explained above, without any weighting. This matrix is found in Table 1 of Appendix B. Each value along the diagonal indicates how many transformers exhibit the principle or facilitator in question. For example, by finding the intersection of the row and column for *Inflate*, we find that this facilitator occurs 164 times in the repository, which matches our observation from the repository itself. The off-diagonal terms indicate how many times two given principles or facilitators occur together in a product. For example, by finding the intersection of the row for *Expand/Collapse* and the column for *Fuse/Divide*, we find that 64 of the 190 products incorporated both principles into their transformations.

This matrix gives an easy way to look at the prevalence of principles and facilitators across the repository through the values on the diagonal. Relationships between facilitators begin to appear, but they are largely obscured due to the large range of frequency. Facilitators that appear less frequently in the repository will have actual interactions overshadowed by more prevalent facilitators. Because of this, techniques for weighting the matrix were explored.

5.3 PERCENTAGE-NORMALIZED PF MATRIX

Several weighting schemes were tried in this study. These include normalizing the entire matrix by its largest value and normalizing each row and column separately by its L1 or L2 norm (the sum or the square root of the sum of the squares, respectively). The most revealing normalization method proved to be a percentage normalization. The percentage-normalized matrix (Table 2 of Appendix B) is asymmetric, unlike its symmetric predecessor. This matrix is computed by weighting each cell by the total products of the row facilitator:

$$\Phi_{ab} = \frac{1}{W_a}\sum_{i=1}^{n}(R_{ia}R_{ib}), \quad where \quad W_a = \sum_{k=1}^{n}(R_{ia})$$

The resulting normalized matrix has values of 1 along the diagonal. The value in each off-diagonal cell indicates the percentage of products using the row facilitator that also use the column facilitator. For instance, the intersection of row *Inflate* and column *Shell* has a value of 0.79, meaning that out of all inflating transformers, 79% also incorporate the concept of shelling. However, by following the opposite route, along the row *Shell* and the column *Inflate*, the value is only 0.08. This means that out of all products that use *Shell*, a mere 8% also employ *Inflate*. This leads to the important (and obvious, in this case) observation that while most inflating transformers make use of shelling (such as embedding a fluid within the expanding material), there are many additional instances of shelling that have nothing to do with inflation.

The percentage-normalized facilitator-facilitator matrix is extremely useful in determining positive relationships between different principles and facilitators. However, it does not clearly show negative correlations, or exclusivity. This is because different facilitators may appear in the same product, while actually relating to different, independent stages of the transformation. This overlap artificially increases some of the values, glossing over what should be clear trends in the data. To help improve this resolution, two additional techniques were investigated.

Figure 4. Three states of the Croozer 535 child carrier: (1) storage, (2) bicycle trailer, and (3) jogging stroller [31].

5.4 SEPARATION OF PROCESSES AND PRINCIPLES

First, the original repository was updated to separate each distinct transformation process. Many transformers, especially those with more than two states, incorporate several separate transformation processes in their design. Figure 4 shows a stroller/bike trailer with three states. Transforming from a stroller to a trailer (mostly *Fuse/Divide* by removing front wheel and adding trailer hitch) employs a different and unrelated set of facilitators than transforming from a stroller to storage (mostly *Expand/Collapse* and *Expose/Cover* by folding and nesting the main structure, plus *Fuse/Divide* to remove the wheels). These different sets include facilitators that have no real relationship to each other functionally, but were grouped together in the original repository. Creating a separate entry for each process helps lessen this deceptive over-correlation.

A second step to delineate true relationships was to also separate each transformer into its basic principles. As mentioned above, the stroller/storage transformation for the product in Fig. 4 utilizes all three principles, even in one process. By isolating each principle into its own entry in the repository, the actual relationship between facilitators and their encompassing principles can be clarified, and the circumstantial, non-functional relationships can be stripped away. Both separation of processes and isolation of principles were used to form a new, revised repository.

The combination of these two techniques effectively decouples much of the information in the PF matrices. Because many products are now counted multiple times, the new unweighted matrix skews the popularity of facilitators. However, the percentage-normalized matrix (Table 3 of Appendix B) provides greatly improved clarity, reducing several values that were previously artificially high.

The success of this separation can be demonstrated by the results for the facilitator *Flip* and its correlation with the three principles (Table 4). From intuition and observation, one might expect *Flip* to occur most frequently in conjunction with *Expose/Cover*, since the flipping action is a straightforward way to expose a new surface. *Flip* may also find use in *Expand/Collapse*, as components are folded or flipped out into a deployed state. *Fuse/Divide* would have limited use for the facilitator. Yet in the original PF matrix, over half of all flipping products are associated with *Fuse/Divide*. By separating the processes into separate entries, the link between *Flip* and *Fuse/Divide* grows much weaker. After isolating the separate principles as well, the correlation with *Expand/Collapse* drops, matching the expectation above that *Flip* would be primarily associated with *Expose/Cover*. Notably, some products still do make use of *Flip* to facilitate the other principles: 21% of products use *Flip* specifically to aid *Expand/Collapse*. This data is much more quantifiable than the vague trend shown in the original matrix, and can be analyzed with greater confidence to discover how the facilitator does aid the other principles in such examples.

Table 4. Percentage of products exhibiting the facilitator *Flip* that are associated with each principle, over three variations of the PF matrix.

Entry for *Flip* in:	*Expand/ Collapse*	*Expose/ Cover*	*Fuse/ Divide*
Original PF matrix	0.70	0.97	0.52
Matrix with processes separated	0.72	0.90	0.30
Matrix with principles separated	0.21	0.76	0.03

6. INTERPRETATION OF FINDINGS

Using the proposed research questions as a guide, we undertake to discover what insights the transformer repository and the subsequent analysis may yield.

Table 5. Prevalence of domains, principles, and facilitators in the transformer repository.

Most common domains	*Tools* (34%), *Structures* (25%), *Vehicles* (20%), *Storage* (11%)
Most common principle	*Expose / Cover* (83%)
Most common principle pair	*Expand / Collapse* with *Expose / Cover* (59%)
Most common facilitators	*Conform with Structural Interfaces* (85%), *Segment* (78%), *Shell* (73%), *Share Functions* (72%)
Least common facilitators	*Inflate* (7%), *Furcate* (12%), *Interchange Working Organ* (14%)

Does the current set of principles and facilitators form a complete basis for all transformers? As mentioned at the beginning of Section 5, no transformer encountered thus far has been seen to fall outside the space described by the current set of principles and facilitators. However, continued refinement of the definitions may clarify the correct location in the space for more complex transformers, including biological examples and primarily electrical systems.

What domains are transformer-rich? The domain of tools (including consumer electronics, appliances and related products) displays a clear lead in the repository. The exact frequency may be slightly inflated due to a possible bias in the sources consulted, but in general, the domains of tools, structures (including furniture and buildings), storage, and vehicles seem to be very popular candidates for transformer design (Table 5).

What principles and facilitators are most dominant? As shown in Table 5, the most prevalent principle is *Expose/Cover*. Upon review of the compiled transformers, a great majority of them incorporate some sort of exposing or covering a feature, part, or interface. The definition is wide enough to cover almost any transformation other than simple change in size (only *Expand/Collapse*) or simple addition of parts (only *Fuse/Divide*). In general, the very idea of using transformation to deliver multiple configurations to the user will be tied to *Expose/Cover*.

The facilitator that clearly dominates the space is *Conform with Structural Interfaces*. This is also broadly defined, and includes all examples of motion being constrained by the structure of either the environment or part of the device itself. Since mechanical transformation is exceptionally dependent on controlling the motion of all or part of the device, it is not surprising that *Conform with Structural Interfaces* is so ubiquitous. The only times that this facilitator is more frequently absent are when the facilitators *Enclose*, *Flip*, or *Inflate* are present (best shown in Table 4 of Appendix D). These facilitators represent transformations that do not necessarily need to be externally controlled: simply flipping a pencil upside-down to expose an eraser is a user action that does not depend heavily on external constraints.

After this facilitator, the facilitators *Segment*, *Shell*, and *Share Functions* are the three most common throughout the design space. These are generic, standard tools in transformer design, and applicable over a wide variety of processes in conjunction with all three principles.

The three least common facilitators in the repository are *Inflate*, *Furcate*, and *Interchange Working Organ*. The first two facilitators can be complicated to implement and can traditionally lead to drawbacks such as low rigidity and strength and high cost; however, current research is quickly advancing their viability through new manufacturing techniques [29]. The third least common facilitator was a surprise, as we observed *Interchange Working Organ* fairly frequently in products. We believe this deviation is due to the similarity among many devices that implement this facilitator (e.g. lawn edger/trimmer/blowers, cordless drill/screwdrivers, etc.). After recording a number of these transformers in the repository, subsequent examples were more likely to be overlooked or excluded due to their similarity to previous entries. Thus overall, the facilitator was likely underrepresented in the data.

Which principles and facilitators tend to go together? Which don't? The transformers studied tend to use multiple principles and many facilitators to accomplish their transformation processes. Of the principles, the most common pairing is *Expand/Collapse* with *Expose/Cover*. These two principles seem more closely related to each other, while *Fuse/Divide* appears more distinct and independent.

To determine which facilitators are more or less likely to appear with a certain principle, we turn to the principle-separated PF matrix with percentage normalization (Table 3 of Appendix B). With the facilitators mapped to only one principle per process (in general), we are better able to determine not only how common a facilitator is with a principle, but also how exclusively it is linked to only one principle. The sub-matrix with principles as rows and facilitators as columns yields the first answer, while the sub-matrix with facilitator rows and principle columns yields the second answer (remembering that this PF matrix is asymmetric). These results are tabulated in Table 6.

Next, we look at the correlations between facilitators, using the same PF matrix. As with the entries linking facilitators with principles, there are two cells for each pair of facilitators. The first value is the percentage of all transformers with facilitator "A" (row) that also uses facilitator "B" (column), and the second value is the reverse. As was demonstrated in Section 5.4, these values can be quite different, due to the varying breadth of processes the facilitators assist. Notable relationships may have two high values, a high and a low, or two low. To examine those interactions where both cells have very high or low values, we can take the average of the two values and create a "mutuality index," showing the extent that facilitators are mutually linked to each other. This index is shown in Appendix C.

Table 6. Notable correlation between facilitators and principles

	Expand / Collapse	*Expose / Cover*	*Fuse / Divide*
Most prevalent	1. Conform w/ Structural Interfaces 2. Nest 3. Shell 4. Segment	1. Shell 2. Share Functions 3. Flip 4. Fold	1. Segment 2. Conform w/ Structural Interfaces 3. Modularize 4. Share Functions
Least prevalent	1. Interchange Working Organ 2. Utilize Generic Connections 3. Share Power Transmission 4. Inflate	1. Inflate 2. Utilize Generic Connections 3. Furcate 4. Interchange Working Organ	1. Inflate 2. Fan 3. Furcate 4. Roll/Wrap/Coil
Most exclusive	1. Inflate 2. Furcate 3. Utilize Flexible Material 4. Nest	1. Flip	1. Utilize Generic Connections 2. Interchange Working Organ

One facilitator pair was found to have a strong lead in mutual correlation: *Segment* and *Conform with Structural Interfaces* (with an index of 0.78). This close relationship makes sense, because most segmented parts require some sort of regulation to keep them in position, such as connecting pins, geometry, or an interface with the environment. After this pair is a large grouping of pairs with less, but still substantial, correlation (indexes from 0.69 and down). These include *Segment* and *Modularize*, *Nest* and *Conform with Structural Interfaces*, *Segment* and *Shell*, and many others.

The mutuality data can also be used to find what facilitators are seldom found together. In Appendix C, those pairs with a mutuality index below 0.1 are designated with an X in the second table. These pairs may be incompatible, unrelated, or simply under-used. Of note are two *Fuse/Divide* exclusive facilitators, *Interchange Working Organ* and *Utilize Generic Connections*. Both have low indexes with the facilitators *Enclose*, *Fan*, *Fold*, *Furcate*, *Inflate*, and *Telescope*, which are all aligned more with the principles *Expand/ Collapse* and *Expose/Collapse*. These are examples where the facilitators relate to different kinds of processes, and are largely unrelated. In contrast, *Enclose* and *Fan* also have a low index. This is because they are actually very similar in definition, but are largely exclusionary of each other: one occurs in three dimensions, the other in two. Finally, some combinations with low indexes may be feasible, but merely unexplored, such as using *Inflate* or *Roll/Wrap/Coil* with *Interchange Working Organ*.

The third set of interest, pairs with only one high value, includes many sets of facilitators where one is necessary or typical for the other, but not the other way. An example was given previously, where *Inflate* almost always includes *Shell*, but only a small portion of *Shell* appears with *Inflate*. These "one-way" interactions may signify causal or dependent relationships, and will be explored below.

Are there interesting groups or chains of facilitators? What are the exceptions? By examining the percentage-normalized PF matrix (Table 3 of Appendix B) row-by-row and extract the high correlations for each facilitator (we use a threshold of 75% here) we can find both mutual and one-way correlations. After the leading correlations for each facilitator have been compiled, the groups can be combined into chains that begin to exhibit a hierarchy. For example, the facilitator *Interchange Working Organ* has correlations with four other facilitators ranking above 90%: *Modularize*, *Segment*, *Share Core Structure*, and *Share Power Transmission*. The rows for these facilitators show additional interaction: *Share Power Transmission* has its own group under it (*Modularize*, *Segment*, *Share Functions*), and *Modularize* and *Share Core Structure* both lead to *Segment*. Because these correlations are not significant going the other direction, chains of supporting facilitators under higher-level facilitators begin to develop. Table 7 shows some example groups or chains discovered through this process. In addition to including correlations above 75%, the table lists notable interactions that measure between 50% and 75% in parentheses.

Table 7. Example facilitator "chains" used in transformers

- *Fan ➔ Fold, Shell (Segment, Conform with Struct. Int., Nest)*
- *Furcate ➔ Conform with Structural Interfaces (Fold, Segment)*
- *Inflate ➔ Utilize Flexible Material (Shell, Nest)*
- *Interchange Working Organ ➔ Share Power Transmission ➔ Share Core Structure, Modularize ➔ Segment (Conform with Structural Interfaces, Share Functions)*
- *Utilize Generic Connections ➔ Modularize ➔ Conform with Structural Interfaces, Segment*

Despite their prevalence, these chains are not absolute rules for excellent transformer design. In fact, innovative transformers are often successful by deliberately ignoring or going against the prevalent trends. One example is the bistable slap bracelet, popular in the 1990s (Fig. 5). Most transformers furcate using folding, segmented joints, perhaps driven by a spring, like an umbrella. Slap bracelets gained the public eye by snapping between two states in a much smoother, sleeker manner, making use of the facilitators *Utilize Composite* (bi-stable metal core), *Roll/Wrap/Coil*, *Utilize Flexible Material*, and *Nest*.

Much of the ongoing research in transforming, deployable, and flexible structures relates to substituting more conventional, rigid-body kinematics facilitators like *Fold* and *Segment* in the chains with more complex but elegant solutions like *Roll/Wrap/Coil*, *Inflate*, and *Utilize Flexible Material* [7,32]. Memory materials, compliant mechanisms, and similar technologies have much to offer in creating transformers with more diverse states, yet fewer moving parts.

Figure 5. Bistable slap bracelet [33].

Can the three indicators of transformation-readiness be verified? All examples in the repository do seem to follow the indicators explained in Section 2.3. Namely, the product has storage or portability needs, combines two closely related and similar systems for convenience, or combines two seemingly unrelated products with underlying functional similarity. This validates that transformers tend to fall under these indicators. However, this does not sufficiently prove that any product demonstrating one of the indicators should involve transformation. Additional non-transforming devices, and perhaps even badly designed or unnecessary transformers, should also be studied to see if the indicators mark a clear boundary between what should and should not transform.

How does this information help design better transformers? The transformer repository developed here gives designers a more concrete basis for transformer design than merely using intuition. It provides a benchmark of what kinds of transformers are already available on the market. It can also be used as a tool in Design by Analogy, focusing specifically on transforming examples. If a designer knows that he wants to create a piece of furniture that transforms into a storage state and conceals part of its structure, he can search the repository for items in the domain *Structure* that exhibit the principles *Expand/Collapse* and *Expose/Cover*. This will give the designer not only a list of similar products, but also an overview of the underlying facilitators common in that type of transformation. Then the designer would be free to either incorporate those facilitators and create a product with known, tested characteristics, or look for ways to break out of the common mold and find innovative new solutions.

Similarly, the PF matrices and mutuality indexes can provide a guide of how transformers typically behave. A designer may look at the table of mutuality indexes (Appendix E) and discover that *Roll/Wrap/Coil* is seldom used with the principles *Interchange Working Organ* and *Share Power Transmission*. One available principle in TIPS for resolving conflicts is to “increase curvature or spheroidality” [9]. The designer can then consider whether this absence of correlation occurs for a reason of incompatibility, or if it represents a new opportunity for innovation.

Finally, this study helps to validate the underlying theory of design methodology being developed for transformation. We have provided significant evidence that the current set of principles and facilitators can satisfactorily describe at least a vast majority of common transformers. Many of these facilitators can be firmly linked to specific principles and correlated facilitators. Trends in both their frequency and their interactions are observable and predictable. This validation will help advance transformer design into a viable, proven method for deciding when and how to incorporate transformation into a concept.

7. CASE STUDY: TRANSFORMING SHOWER

A simple case study illustrates how a designer may use the transformer repository to improve design. Consider the interior furniture and fixtures in a recreational vehicle. Many RVs include a small bathroom with a toilet, sink, and shower. Space is a prime consideration in the bathroom’s design and features. A designer may wish to explore the possibility of transforming the shower area into a feature not currently available in most RVs, such as a full-size bathtub, washing machine, or dryer.

The transformer repository can help the designer learn what facilitators may help him and find examples of similar products. We begin by sorting the repository by three categories: the domain *Structure* (or furniture), and the principles *Expand/Collapse* and *Expose/Cover*. This gives a list of 19 products that fall under all three categories. A PF matrix can be constructed for only these 19 rows, yielding the principle and facilitator interactions specific to this domain and principle subset (Appendix D). From these matrices, we learn that in addition to *Expand/Collapse* and *Expose/Cover*, the principle *Fuse/Divide* is also usually used in these products. The facilitators *Conform with Structural Interfaces*, *Nest*, *Segment*, *Share Functions*, and *Shell* are all used in most or all of the products, with *Flip*, *Fold*, *Modularize*, and *Share Core Structure* also playing major roles. We also can examine the products for inspiration and implantation of Design by Analogy techniques (Fig 6).

Figure 6. Analogous products to the transforming shower: A chair/table set [34], a foldout house [35], a sofa/bunk bed [36], a desk/end table [37], a window/balcony [38].

This information may suggest to the designer a system with a central core and numerous modules that nest and fold out, with a high level of function sharing also involved. The solution might be similar to the concept in Fig 7.

Figure 7. "Flight" convertible shower/bath/wash table [39].

In this concept, the upper portion of the shower module divides and folds out into a bathtub, which is supported on the wash table area. The same faucet fills the sink and the bathtub. This concept, designed by Isabelle Hauser, exhibits all of the principles and facilitators listed above, along with *Enclose* and *Share Power Transmission* (through a shared water supply). The finished concept is innovative and compact, yet simple to operate. The repository was able to predict the facilitators that would result in a useful, useable transformer.

8. CONCLUSION

Transforming products are diverse in background and sometimes complex in behavior. Their underlying principles, however, are consistent and generally easy to understand. A better understanding of how transformers are currently designed will enable designers to reach greater potential in creating new ways to fill customer needs.

The research in this paper validates and advances previous research done in transformer design. Using empirical, quantifiable methods, we have confirmed that the current set of principles and facilitators are accurate and meaningful in describing transformation processes. We have also inductively demonstrated the existence of consistent, observable trends and relationships among domains, principles, and facilitators. This information will allow further refinement and development of a transformer design methodology.

Now that these associations have been established, we can examine what kind of hierarchy and causality may be present. The possible relationships between facilitators and function structure also need to be explored. Future research will attempt to assemble this information into a repeatable method for designing transformers, including steps to determine when transformation should be used, how to create appropriate states from customer needs, and how to assemble a transformation process between states based on functional modeling and the information in this repository. The result will be a method that can be used over a wide variety of domains and will consistently yield transforming products that are elegant, flexible, and easy to use.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support provided from the Cullen Endowed Professorship in Engineering, The University of Texas at Austin, and grants from the Air Force Research Laboratory Munitions Directorate (AFRL/MN) at Eglin, Florida and the Air Force Office of Scientific Research (AFOSR). The authors would also like to thank the Department of Engineering Mechanics at the U.S. Air Force Academy for their support and guidance, as well as the Thrust 2000/Cockrell Engineering Fellowship for additional support. Any opinions, findings, or conclusions found in this paper are those of the authors and do not necessarily reflect the views of the sponsors.

REFERENCES

1. Singh, V., Skiles, S. M., Krager, J. E., Wood, K. L., Jensen, D., and Szmerekovsky, A., 2006, “Innovations in Design Through Transformation: A Fundamental Study of Transformation Principles”, DETC-2006-99575, *International Design Engineering Technical Conferences*, Philadelphia.

2. Mollerup P., 2001, *Collapsible: The Genius of Space Saving*, Chronicle Books, San Francisco.

3. The Fletcher Capstan Table, 2007, http://www.dbfletcher.com/capstan/

4. Siddiqi, A., de Weck, O., 2006, “Self-similar modular architectures for reconfigurable space systems,” *IAC-06-D1.4.3*.

5. Siddiqi, A., de Weck, O., 2006, “Reconfigurability in planetary surface vehicles: Modeling approaches and case study,” *Journal of the British Interplanetary Society*, **59**.

6. Mehrabi, M. G., Ulsoy, A. F., Koren, Y., 2000, “Reconfigurable manufacturing systems and their enabling technologies,” *International Journal of Manufacturing Technology and Management*, **13** (2).

7. Gantes, C. J., 2001, *Deployable Structures, Analysis and Design*, WIT Press, Billerica.

8. Kubalsky, A., 2007, Interview, “Transformers’ Toy Design,” *PingMag*, http://www.pingmag.jp/2007/06/29/transformers

9. Hauser, J. and Clausing D., 1988, “The House of Quality,” *Harvard Business Review*, May-June, pp. 63-73.

10. Clausing, D., 1994, *Quality Function Deployment*, MIT Press, Cambridge.

11. Otto, K. and Wood, K. L., 2001, *Product Design: Techniques in Product Design and New Product Development*, Prentice-Hall, Upper Saddle River.

12. Altshuller, G. S., 1984, *Creativity as an Exact Science: The Theory of the Solution of Inventive Problems*, Gordon and Breach, Brussels.

13. Stone, R. B., Wood, K. L., Crawford, R. H., 1999, "Product Architecture Development With Quantitative Functional Models," DETC99/DTM-8764, *ASME Design Engineering Technical Conferences*, Las Vegas.

14. Hirtz, J., Stone, R. B., McAdams, D. A., Szykman, S., Wood, K. L., 2002, "A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts," *Research in Engineering Design*, **13** (2), pp. 65-82.

15. Linsey, J., Laux, J., Clauss, E., Wood, K. L., Markman, A., 2007, "Increasing Innovation: A Trilogy of Experiments Towards a Design-By-Analogy Method," DETC-2007-34948, *International Design Engineering Technical Conferences*, Las Vegas.

16. French, M., 1996, *Conceptual Design*, Springer-Verlag, London.

17. Linsey, J., Murphy, J., Wood, K. L., Markman, A., Kurtoglu, T., 2006, "Representing Analogies: Increasing the Probability of Success," *Proceedings of ASME Design Theory and Methodology Conference*, Philadelphia.

18. Singh, V., Walther, B., Krager, J., Putnam, N., Koraishy, B., Wood, K. L., Jensen, D., 2007, "Design for Transformation: Theory, Method, and Application," DETC-2007-34876, *International Design Engineering Technical Conferences*, Las Vegas.

19. Skiles, S., 2006, "Development of Principles and Facilitators for Transformational Product Design," The University of Texas, Austin.

20. Singh, V. 2007, "Design for Transformation: Design Principles and Approach with Concept Generation Tools and Techniques," The University of Texas, Austin.

21. Inflatable Antenna Experiment, 2007, http://www.lgarde.com/gsfc/207.htm

22. Hypno Skates, 2007, http://www.hypnoskates.com

23. Gentleman's Cane Swords, 2007, http://www.gungfu.com/pics_info_pages/swords_cane_gentleman.htm

24. "The Sharper Image Catalog," Dec. 2007, The Sharper Image, San Francisco.

25. Asus R1 Tablet PC, 2007, seen at Best Buy, Austin, Texas.

26. George Foreman G5 Electric Grill with 5 Replaceable Plates, 2007, seen at Target, Austin, Texas.

27. *Yanko Design – Modern Industrial Design News*, 2008, http://www.yankodesign.com

28. *Coolest Gadgets – Reporting on the Latest Cool Gadgets*, 2007, http://www.coolest-gadgets.com

29. "Stent Procedure – Balloons and Stents," 2008, *Angioplasty.org*, http://www.ptca.org/devices4.html

30. Shanghai Qizhong Forest Sports City Tennis Center, 2007, http://www.yankodesign.com/index.php/2007/11/07/mitsurus-magnolia-stadium/

31. Croozer 535 child carrier, 2007, http://www.croozerdesigns.com/croozer_kid.html

32. Maheshwaraa, U., Bourell, D., Seepersad, C., 2007, "Design and Freeform Fabrication of Deployable Structures with Lattice Skins", *Rapid Prototyping Journal*, **13** (4), pp. 213-225.

33. Kebadze, E., Guest, S. D., and Pellegrino, S., 2004, *Bistable Prestressed Shell Structures*, International Journal of Solids and Structures.

34. KEWB flexible furniture, 2007, http://www.kewb.co.uk/home1.html

35. Push Button House, 2007, http://www.illy.com/wps/wcm/connect/US/illy/art/project/push-button-house/

36. Doc bunk bed sofa, 2007, http://www.bonbon.co.uk/clei/doc.htm

37. TIMO smart table, 2007, http://gredogo17.ba.ro/

38. Bloomframe dynamic balcony, 2007, http://www.hofmandujardin.nl/index2.html

39. Flight supercompact bathroom, 2007, http://www.yankodesign.com/index.php/2007/08/22/supercompact-bathroom

APPENDIX A

TRANSFORMATION PRINCIPLES AND FACILITATORS

Principles	*Expand / Collapse*	Change physical dimensions of an object to bring about an increase/decrease in occupied volume primarily along an axis, in a plane, or in three dimensions
	Expose / Cover	Reveal or conceal a new surface to alter functionality
	Fuse / Divide	Make a single functional device become two or more devices (discretization), at least one of which has its own distinct functionality defined by the state of the transformer, or vice versa
Facilitators	*Conform with Structural Interfaces*	Statically or dynamically constrain the motion of a component using structural interfaces
	Enclose	Manipulate object in three dimensions in order to enclose a three-dimensional space
	Fan	Manipulate object in two dimensions to create an elongation, planar spread, or enclosed space to alter its function
	Flip	Perform different functions based on the orientation of the object
	Fold	Create relative motion between parts or surfaces by hinging, bending or creasing
	Furcate	Change between two or more discrete, stable states determined by the boundary conditions
	Inflate	Fill an enclosed space, constructed of flexible material, with fluid media to change geometry and function
	Interchange Working Organ	Interchange working organ to produce a different end effect
	Modularize	Localize related functions into product modules
	Nest	Place an object inside another object, wholly or partially, wherein the internal geometry of the containing object is similar to the external geometry of the contained object
	Roll/Wrap/Coil	Bring about a change in an object's functionality by manipulating its geometrical surfaces around an axis to create or enhance spheroidality and curvature
	Segment	Divide single contiguous part into two or more parts
	Share Core Structure	Device's core structure remains the same, while the periphery reconfigures to alter the function of the device
	Share Functions	Perform two or more discrete functions
	Share Power Transmission	Transmit power from a common source to perform different functions in different configurations
	Shell	Embed an element in a device, where the element performs a different function
	Telescope	Manipulate an object along an axis to create elongation, planar spread or enclosure to alter its function
	Utilize Composite	Form a functional part from two or more non-functional parts
	Utilize Flexible Material	Change object dimensions with change in boundary conditions
	Utilize Generic Connections	Employ internal or external connections (structural, power) that can be used by different modules to perform different functions or perform the same function in a different way

APPENDIX B

PF MATRICES

Table B - 1. Unweighted PF matrix.

	Expand / Collapse	Expose / Cover	Fuse / Divide	Conform w/ Struct. Int.	Enclose	Fan	Flip	Fold	Furcate	Inflate	Interchange Working Organ	Modularize	Nest	Roll/Wrap/Coil	Segment	Share Core Structure	Share Functions	Share Power Transmission	Shell	Telescope	Utilize Composite	Utilize Flexible Material	Utilze Generic Connections
Expand / Collapse	125	117	64	110	50	53	78	89	22	14	10	72	101	31	95	60	90	27	107	31	40	53	12
Expose / Cover	117	160	83	139	51	53	108	101	23	13	13	105	117	35	123	81	124	39	127	33	48	56	20
Fuse / Divide	64	83	108	99	23	29	58	54	11	4	23	86	75	12	104	59	82	39	83	21	33	16	42
Conform w/ Struct. Int.	110	139	99	164	49	49	97	97	23	8	26	113	114	30	139	88	122	47	127	28	49	45	40
Enclose	50	51	23	49	55	11	36	37	8	9	3	32	41	20	38	22	43	7	44	11	17	33	6
Fan	53	53	29	49	11	56	38	46	13	4	4	33	47	16	45	28	39	17	51	7	20	21	3
Flip	78	108	58	97	36	38	111	84	18	3	10	78	72	19	91	58	91	31	80	11	33	32	15
Fold	89	101	54	97	37	46	84	106	19	7	11	68	79	18	88	54	84	31	85	15	34	37	8
Furcate	22	23	11	23	8	13	18	19	23	0	0	12	17	6	15	10	19	6	18	1	4	11	1
Inflate	14	13	4	8	9	4	3	7	0	14	1	6	9	9	5	8	10	2	11	2	2	14	1
Interchange Working Organ	10	13	23	26	3	4	10	11	0	1	27	26	14	3	27	26	21	26	16	3	5	3	18
Modularize	72	105	86	113	32	33	78	68	12	6	26	128	82	17	113	86	96	49	93	23	32	27	40
Nest	101	117	75	114	41	47	72	79	17	9	14	82	125	28	103	60	94	29	125	31	43	42	21
Roll/Wrap/Coil	31	35	12	30	20	16	19	18	6	9	3	17	28	37	20	18	24	6	31	6	14	31	4
Segment	95	123	104	139	38	45	91	88	15	5	27	113	103	20	149	86	111	49	116	28	49	30	41
Share Core Structure	60	81	59	88	22	28	58	54	10	8	26	86	60	18	86	102	79	39	70	18	23	31	30
Share Functions	90	124	82	122	43	39	91	84	19	10	21	96	94	24	111	79	139	45	104	25	36	44	31
Share Power Transmission	27	39	39	47	7	17	31	31	6	2	26	49	29	6	49	39	45	54	31	8	10	7	20
Shell	107	127	83	127	44	51	80	85	18	11	16	93	125	31	116	70	104	31	140	32	47	46	26
Telescope	31	33	21	28	11	7	11	15	1	2	3	23	31	6	28	18	25	8	32	36	13	13	4
Utilize Composite	40	48	33	49	17	20	33	34	4	2	5	32	43	14	49	23	36	10	47	13	54	14	13
Utilize Flexible Material	53	56	16	45	33	21	32	37	11	14	3	27	42	31	30	31	44	7	46	13	14	61	5
Utilze Generic Connections	12	20	42	40	6	3	15	8	1	1	18	40	21	4	41	30	31	20	26	4	13	5	43

0 - 25 %	(white)
25 - 50 %	(yellow)
50 - 75 %	(green)
50 - 100 %	(blue)

Table B - 2. Percentage-normalized PF matrix.

	Expand / Collapse	Expose / Cover	Fuse / Divide	Conform w/ Struct. Int.	Enclose	Fan	Flip	Fold	Furcate	Inflate	Interchange Working Organ	Modularize	Nest	Roll/Wrap/Coil	Segment	Share Core Structure	Share Functions	Share Power Transmission	Shell	Telescope	Utilize Composite	Utilize Flexible Material	Utilze Generic Connections
Expand / Collapse	1.00	0.94	0.51	0.88	0.40	0.42	0.62	0.71	0.18	0.11	0.08	0.58	0.81	0.25	0.76	0.48	0.72	0.22	0.86	0.25	0.32	0.42	0.10
Expose / Cover	0.73	1.00	0.52	0.87	0.32	0.33	0.67	0.63	0.14	0.08	0.08	0.66	0.73	0.22	0.77	0.51	0.77	0.24	0.79	0.21	0.30	0.35	0.13
Fuse / Divide	0.59	0.77	1.00	0.92	0.21	0.27	0.54	0.50	0.10	0.04	0.21	0.80	0.69	0.11	0.96	0.55	0.76	0.36	0.77	0.19	0.31	0.15	0.39
Conform w/ Struct. Int.	0.67	0.85	0.60	1.00	0.30	0.30	0.59	0.59	0.14	0.05	0.16	0.69	0.70	0.18	0.85	0.54	0.74	0.29	0.77	0.17	0.30	0.27	0.24
Enclose	0.91	0.93	0.42	0.89	1.00	0.20	0.65	0.67	0.15	0.16	0.05	0.58	0.75	0.36	0.69	0.40	0.78	0.13	0.80	0.20	0.31	0.60	0.11
Fan	0.95	0.95	0.52	0.88	0.20	1.00	0.68	0.82	0.23	0.07	0.07	0.59	0.84	0.29	0.80	0.50	0.70	0.30	0.91	0.13	0.36	0.38	0.05
Flip	0.70	0.97	0.52	0.87	0.32	0.34	1.00	0.76	0.16	0.03	0.09	0.70	0.65	0.17	0.82	0.52	0.82	0.28	0.72	0.10	0.30	0.29	0.14
Fold	0.84	0.95	0.51	0.92	0.35	0.43	0.79	1.00	0.18	0.07	0.10	0.64	0.75	0.17	0.83	0.51	0.79	0.29	0.80	0.14	0.32	0.35	0.08
Furcate	0.96	1.00	0.48	1.00	0.35	0.57	0.78	0.83	1.00	0.00	0.00	0.52	0.74	0.26	0.65	0.43	0.83	0.26	0.78	0.04	0.17	0.48	0.04
Inflate	1.00	0.93	0.29	0.57	0.64	0.29	0.21	0.50	0.00	1.00	0.07	0.43	0.64	0.64	0.36	0.57	0.71	0.14	0.79	0.14	0.14	1.00	0.07
Interchange Working Organ	0.37	0.48	0.85	0.96	0.11	0.15	0.37	0.41	0.00	0.04	1.00	0.96	0.52	0.11	1.00	0.96	0.78	0.96	0.59	0.11	0.19	0.11	0.67
Modularize	0.56	0.82	0.67	0.88	0.25	0.26	0.61	0.53	0.09	0.05	0.20	1.00	0.64	0.13	0.88	0.67	0.75	0.38	0.73	0.18	0.25	0.21	0.31
Nest	0.81	0.94	0.60	0.91	0.33	0.38	0.58	0.63	0.14	0.07	0.11	0.66	1.00	0.22	0.82	0.48	0.75	0.23	1.00	0.25	0.34	0.34	0.17
Roll/Wrap/Coil	0.84	0.95	0.32	0.81	0.54	0.43	0.51	0.49	0.16	0.24	0.08	0.46	0.76	1.00	0.54	0.49	0.65	0.16	0.84	0.16	0.38	0.84	0.11
Segment	0.64	0.83	0.70	0.93	0.26	0.30	0.61	0.59	0.10	0.03	0.18	0.76	0.69	0.13	1.00	0.58	0.74	0.33	0.78	0.19	0.33	0.20	0.28
Share Core Structure	0.59	0.79	0.58	0.86	0.22	0.27	0.57	0.53	0.10	0.08	0.25	0.84	0.59	0.18	0.84	1.00	0.77	0.38	0.69	0.18	0.23	0.30	0.29
Share Functions	0.65	0.89	0.59	0.88	0.31	0.28	0.65	0.60	0.14	0.07	0.15	0.69	0.68	0.17	0.80	0.57	1.00	0.32	0.75	0.18	0.26	0.32	0.22
Share Power Transmission	0.50	0.72	0.72	0.87	0.13	0.31	0.57	0.57	0.11	0.04	0.48	0.91	0.54	0.11	0.91	0.72	0.83	1.00	0.57	0.15	0.19	0.13	0.37
Shell	0.76	0.91	0.59	0.91	0.31	0.36	0.57	0.61	0.13	0.08	0.11	0.66	0.89	0.22	0.83	0.50	0.74	0.22	1.00	0.23	0.34	0.33	0.19
Telescope	0.86	0.92	0.58	0.78	0.31	0.19	0.31	0.42	0.03	0.06	0.08	0.64	0.86	0.17	0.78	0.50	0.69	0.22	0.89	1.00	0.36	0.36	0.11
Utilize Composite	0.74	0.89	0.61	0.91	0.31	0.37	0.61	0.63	0.07	0.04	0.09	0.59	0.80	0.26	0.91	0.43	0.67	0.19	0.87	0.24	1.00	0.26	0.24
Utilize Flexible Material	0.87	0.92	0.26	0.74	0.54	0.34	0.52	0.61	0.18	0.23	0.05	0.44	0.69	0.51	0.49	0.51	0.72	0.11	0.75	0.21	0.23	1.00	0.08
Utilze Generic Connections	0.28	0.47	0.98	0.93	0.14	0.07	0.35	0.19	0.02	0.02	0.42	0.93	0.49	0.09	0.95	0.70	0.72	0.47	0.60	0.09	0.30	0.12	1.00

0 - 25 %	(white)
25 - 50 %	(yellow)
50 - 75 %	(green)
50 - 100 %	(blue)

Table B - 3. Percentage-normalized PF matrix with transformation processes and principles isolated.

	Expand / Collapse	Expose / Cover	Fuse / Divide	Conform w/ Struct. Int.	Enclose	Fan	Flip	Fold	Furcate	Inflate	Interchange Working Organ	Modularize	Nest	Roll/Wrap/Coil	Segment	Share Core Structure	Share Functions	Share Power Transmission	Shell	Telescope	Utilize Composite	Utilize Flexible Material	Utilize Generic Connections
Expand / Collapse	1.00	0.00	0.00	0.85	0.26	0.47	0.22	0.71	0.18	0.12	0.00	0.19	0.82	0.28	0.71	0.41	0.33	0.07	0.74	0.22	0.26	0.45	0.02
Expose / Cover	0.00	1.00	0.00	0.21	0.24	0.18	0.69	0.59	0.01	0.01	0.05	0.55	0.12	0.12	0.47	0.41	0.71	0.19	0.76	0.13	0.15	0.07	0.01
Fuse / Divide	0.00	0.00	1.00	0.89	0.04	0.01	0.05	0.07	0.01	0.00	0.29	0.82	0.14	0.02	0.93	0.58	0.74	0.35	0.51	0.06	0.27	0.05	0.54
Conform w/ Struct. Int.	0.51	0.15	0.35	1.00	0.15	0.26	0.24	0.48	0.11	0.03	0.11	0.49	0.53	0.15	0.82	0.49	0.55	0.21	0.65	0.14	0.26	0.23	0.21
Enclose	0.47	0.49	0.04	0.44	1.00	0.07	0.49	0.66	0.08	0.11	0.01	0.33	0.41	0.34	0.47	0.34	0.51	0.01	0.75	0.18	0.23	0.37	0.04
Fan	0.67	0.31	0.01	0.64	0.06	1.00	0.40	0.78	0.15	0.06	0.02	0.27	0.57	0.21	0.69	0.44	0.43	0.15	0.78	0.07	0.25	0.28	0.01
Flip	0.21	0.76	0.03	0.38	0.26	0.26	1.00	0.74	0.07	0.02	0.06	0.57	0.20	0.09	0.59	0.43	0.71	0.20	0.69	0.07	0.20	0.12	0.04
Fold	0.49	0.48	0.03	0.56	0.26	0.37	0.55	1.00	0.10	0.04	0.03	0.40	0.45	0.14	0.67	0.39	0.58	0.15	0.74	0.11	0.21	0.24	0.01
Furcate	0.88	0.08	0.04	0.92	0.23	0.50	0.38	0.73	1.00	0.00	0.00	0.23	0.65	0.23	0.65	0.42	0.42	0.12	0.58	0.08	0.15	0.42	0.00
Inflate	0.89	0.11	0.00	0.33	0.44	0.28	0.17	0.44	0.00	1.00	0.00	0.28	0.61	0.56	0.17	0.61	0.33	0.06	0.67	0.17	0.22	0.89	0.00
Interchange Working Organ	0.00	0.25	0.75	0.75	0.03	0.06	0.25	0.16	0.00	0.00	1.00	0.97	0.19	0.00	0.97	0.94	0.66	0.91	0.56	0.03	0.13	0.00	0.69
Modularize	0.14	0.47	0.39	0.60	0.14	0.14	0.45	0.42	0.03	0.03	0.18	1.00	0.26	0.06	0.79	0.61	0.69	0.32	0.65	0.11	0.18	0.09	0.25
Nest	0.78	0.13	0.09	0.85	0.22	0.38	0.21	0.62	0.13	0.08	0.04	0.34	1.00	0.24	0.76	0.45	0.46	0.11	0.87	0.24	0.26	0.35	0.08
Roll/Wrap/Coil	0.64	0.32	0.04	0.59	0.45	0.34	0.21	0.46	0.11	0.18	0.00	0.18	0.57	1.00	0.39	0.38	0.38	0.04	0.79	0.13	0.25	0.59	0.04
Segment	0.38	0.30	0.32	0.73	0.14	0.25	0.34	0.52	0.07	0.01	0.13	0.58	0.43	0.09	1.00	0.52	0.59	0.24	0.69	0.15	0.27	0.13	0.19
Share Core Structure	0.32	0.38	0.30	0.65	0.15	0.24	0.36	0.45	0.07	0.07	0.18	0.66	0.37	0.13	0.76	1.00	0.62	0.30	0.63	0.15	0.18	0.19	0.20
Share Functions	0.20	0.51	0.29	0.57	0.17	0.18	0.46	0.51	0.05	0.03	0.10	0.58	0.29	0.10	0.67	0.48	1.00	0.25	0.71	0.10	0.23	0.15	0.16
Share Power Transmission	0.13	0.43	0.43	0.69	0.01	0.19	0.42	0.42	0.04	0.01	0.43	0.85	0.22	0.03	0.85	0.75	0.78	1.00	0.58	0.09	0.16	0.04	0.36
Shell	0.38	0.45	0.17	0.55	0.22	0.27	0.37	0.55	0.06	0.05	0.07	0.45	0.47	0.17	0.66	0.41	0.59	0.15	1.00	0.17	0.25	0.20	0.10
Telescope	0.54	0.37	0.10	0.60	0.25	0.12	0.17	0.38	0.04	0.06	0.02	0.37	0.63	0.13	0.69	0.48	0.42	0.12	0.85	1.00	0.27	0.27	0.06
Utilize Composite	0.42	0.29	0.29	0.71	0.22	0.28	0.35	0.49	0.05	0.05	0.05	0.41	0.46	0.18	0.81	0.37	0.61	0.14	0.81	0.18	1.00	0.20	0.19
Utilize Flexible Material	0.81	0.14	0.06	0.68	0.38	0.35	0.24	0.63	0.15	0.22	0.00	0.22	0.67	0.46	0.43	0.43	0.43	0.04	0.69	0.19	0.22	1.00	0.04
Utilze Generic Connections	0.04	0.02	0.94	0.96	0.06	0.02	0.13	0.02	0.00	0.00	0.46	0.92	0.23	0.04	0.94	0.69	0.69	0.50	0.54	0.06	0.31	0.06	1.00

0 - 25 %	(white)
25 - 50 %	(yellow)
50 - 75 %	(green)
50 - 100 %	(blue)

APPENDIX C

MUTUALITY INDEX

	Conform w/ Struct. Int.	Enclose	Fan	Flip	Fold	Furcate	Inflate	Interchange Working Organ	Modularize	Nest	Roll/Wrap/Coil	Segment	Share Core Structure	Share Functions	Share Power Transmission	Shell	Telescope	Utilize Composite	Utilize Flexible Material	Utilze Generic Connections
Conform w/ Struct. Int.	1.00	0.29	0.45	0.31	0.52	0.52	0.18	0.43	0.54	0.69	0.37	0.78	0.57	0.56	0.45	0.60	0.37	0.48	0.45	0.59
Enclose		1.00	0.06	0.38	0.46	0.16	0.28	0.02	0.23	0.32	0.39	0.30	0.25	0.34	0.01	0.48	0.21	0.22	0.37	0.05
Fan			1.00	0.33	0.57	0.32	0.17	0.04	0.20	0.47	0.28	0.47	0.34	0.30	0.17	0.52	0.09	0.26	0.31	0.02
Flip				1.00	0.64	0.23	0.09	0.15	0.51	0.20	0.15	0.47	0.39	0.59	0.31	0.53	0.12	0.28	0.18	0.08
Fold					1.00	0.42	0.24	0.09	0.41	0.54	0.30	0.59	0.42	0.55	0.28	0.65	0.25	0.35	0.43	0.01
Furcate						1.00	0.00	0.00	0.13	0.39	0.17	0.36	0.25	0.24	0.08	0.32	0.06	0.10	0.29	0.00
Inflate							1.00	0.00	0.15	0.35	0.37	0.09	0.34	0.18	0.04	0.36	0.11	0.14	0.56	0.00
Interchange Working Organ								1.00	0.57	0.12	0.00	0.55	0.56	0.38	0.67	0.32	0.03	0.09	0.00	0.57
Modularize									1.00	0.30	0.12	0.69	0.63	0.63	0.59	0.55	0.24	0.29	0.16	0.58
Nest										1.00	0.40	0.60	0.41	0.37	0.17	0.67	0.44	0.36	0.51	0.16
Roll/Wrap/Coil											1.00	0.24	0.25	0.24	0.03	0.48	0.13	0.21	0.52	0.04
Segment												1.00	0.64	0.63	0.54	0.68	0.42	0.54	0.28	0.56
Share Core Structure													1.00	0.55	0.53	0.52	0.32	0.27	0.31	0.44
Share Functions														1.00	0.51	0.65	0.26	0.42	0.29	0.42
Share Power Transmission															1.00	0.37	0.10	0.15	0.04	0.43
Shell																1.00	0.51	0.53	0.45	0.32
Telescope																	1.00	0.22	0.23	0.06
Utilize Composite																		1.00	0.21	0.25
Utilize Flexible Material																			1.00	0.05
Utilze Generic Connections																				1.00

	Conform w/ Struct. Int.	Enclose	Fan	Flip	Fold	Furcate	Inflate	Interchange Working Organ	Modularize	Nest	Roll/Wrap/Coil	Segment	Share Core Structure	Share Functions	Share Power Transmission	Shell	Telescope	Utilize Composite	Utilize Flexible Material	Utilze Generic Connections
Conform w/ Struct. Int.												✔								
Enclose			X					X							X					X
Fan								X									X			X
Flip							X													X
Fold								X												X
Furcate							X	X							X		X			X
Inflate								X				X								X
Interchange Working Organ											X						X	X	X	
Modularize																				
Nest																				
Roll/Wrap/Coil															X					
Segment																				
Share Core Structure																				
Share Functions																				
Share Power Transmission																			X	
Shell																				
Telescope																				X
Utilize Composite																				
Utilize Flexible Material																				X
Utilze Generic Connections																				

APPENDIX D

CASE STUDY: PF MATRICES FOR TRANSFORMING SHOWER

Table D - 1. Unweighted PF matrix

	Expand / Collapse	Expose / Cover	Fuse / Divide	Conform w/ Struct. Int.	Enclose	Fan	Flip	Fold	Furcate	Inflate	Interchange Working Organ	Modularize	Nest	Roll/Wrap/Coil	Segment	Share Core Structure	Share Functions	Share Power Transmission	Shell	Telescope	Utilize Composite	Utilize Flexible Material	Utilize Generic Connections
Expand / Collapse	19	19	13	19	5	8	11	11	4	1	1	10	17	2	19	13	15	1	18	6	7	3	1
Expose / Cover	19	19	13	19	5	8	11	11	4	1	1	10	17	2	19	13	15	1	18	6	7	3	1
Fuse / Divide	13	13	13	13	3	6	7	7	2	0	0	5	12	1	13	8	10	0	12	5	6	1	1
Conform w/ Struct. Int.	19	19	13	19	5	8	11	11	4	1	1	10	17	2	19	13	15	1	18	6	7	3	1
Enclose	5	5	3	5	5	0	3	3	1	1	0	3	3	1	5	5	5	0	4	1	3	1	1
Fan	8	8	6	8	0	8	6	6	3	0	0	3	8	1	8	6	7	0	8	1	4	2	0
Flip	11	11	7	11	3	6	11	10	4	0	0	6	11	0	11	8	10	0	11	0	4	1	0
Fold	11	11	7	11	3	6	10	11	4	0	0	6	11	0	11	7	11	0	11	1	4	1	0
Furcate	4	4	2	4	1	3	4	4	4	0	0	3	4	0	4	3	4	0	4	0	0	1	0
Inflate	1	1	0	1	1	0	0	0	0	1	0	0	0	1	1	1	1	0	1	0	0	1	0
Interchange Working Organ	1	1	0	1	0	0	0	0	0	0	1	1	1	0	1	1	0	1	1	1	0	0	0
Modularize	10	10	5	10	3	3	6	6	3	0	1	10	9	0	10	7	7	1	9	4	3	1	1
Nest	17	17	12	17	3	8	11	11	4	0	1	9	17	1	17	11	13	1	17	5	6	2	0
Roll/Wrap/Coil	2	2	1	2	1	1	0	0	0	1	0	0	1	2	2	2	2	0	2	0	1	2	0
Segment	19	19	13	19	5	8	11	11	4	1	1	10	17	2	19	13	15	1	18	6	7	3	1
Share Core Structure	13	13	8	13	5	6	8	7	3	1	1	7	11	2	13	13	11	1	12	3	6	3	1
Share Functions	15	15	10	15	5	7	10	11	4	1	0	7	13	2	15	11	15	0	14	3	6	3	1
Share Power Transmission	1	1	0	1	0	0	0	0	0	0	1	1	1	0	1	1	0	1	1	1	0	0	0
Shell	18	18	12	18	4	8	11	11	4	1	1	9	17	2	18	12	14	1	18	5	6	3	0
Telescope	6	6	5	6	1	1	0	1	0	0	1	4	5	0	6	3	3	1	5	6	2	0	1
Utilize Composite	7	7	6	7	3	4	4	4	0	0	0	3	6	1	7	6	6	0	6	2	7	1	1
Utilize Flexible Material	3	3	1	3	1	2	1	1	1	1	0	1	2	2	3	3	3	0	3	0	1	3	0
Utilze Generic Connections	1	1	1	1	1	0	0	0	0	0	0	1	0	0	1	1	1	0	0	1	1	0	1

0 - 25 %	(white)
25 - 50 %	(yellow)
50 - 75 %	(green)
50 - 100 %	(blue)

Table D - 2. Percentage-normalized PF matrix

	Expand / Collapse	Expose / Cover	Fuse / Divide	Conform w/ Struct. Int.	Enclose	Fan	Flip	Fold	Furcate	Inflate	Interchange Working Organ	Modularize	Nest	Roll/Wrap/Coil	Segment	Share Core Structure	Share Functions	Share Power Transmission	Shell	Telescope	Utilize Composite	Utilize Flexible Material	Utilize Generic Connections
Expand / Collapse	1.00	1.00	0.68	1.00	0.26	0.42	0.58	0.58	0.21	0.05	0.05	0.53	0.89	0.11	1.00	0.68	0.79	0.05	0.95	0.32	0.37	0.16	0.05
Expose / Cover	1.00	1.00	0.68	1.00	0.26	0.42	0.58	0.58	0.21	0.05	0.05	0.53	0.89	0.11	1.00	0.68	0.79	0.05	0.95	0.32	0.37	0.16	0.05
Fuse / Divide	1.00	1.00	1.00	1.00	0.23	0.46	0.54	0.54	0.15	0.00	0.00	0.38	0.92	0.08	1.00	0.62	0.77	0.00	0.92	0.38	0.46	0.08	0.08
Conform w/ Struct. Int.	1.00	1.00	0.68	1.00	0.26	0.42	0.58	0.58	0.21	0.05	0.05	0.53	0.89	0.11	1.00	0.68	0.79	0.05	0.95	0.32	0.37	0.16	0.05
Enclose	1.00	1.00	0.60	1.00	1.00	0.00	0.60	0.60	0.20	0.20	0.00	0.60	0.60	0.20	1.00	1.00	1.00	0.00	0.80	0.20	0.60	0.20	0.20
Fan	1.00	1.00	0.75	1.00	0.00	1.00	0.75	0.75	0.38	0.00	0.00	0.38	1.00	0.13	1.00	0.75	0.88	0.00	1.00	0.13	0.50	0.25	0.00
Flip	1.00	1.00	0.64	1.00	0.27	0.55	1.00	0.91	0.36	0.00	0.00	0.55	1.00	0.00	1.00	0.73	0.91	0.00	1.00	0.00	0.36	0.09	0.00
Fold	1.00	1.00	0.64	1.00	0.27	0.55	0.91	1.00	0.36	0.00	0.00	0.55	1.00	0.00	1.00	0.64	1.00	0.00	1.00	0.09	0.36	0.09	0.00
Furcate	1.00	1.00	0.50	1.00	0.25	0.75	1.00	1.00	1.00	0.00	0.00	0.75	1.00	0.00	1.00	0.75	1.00	0.00	1.00	0.00	0.00	0.25	0.00
Inflate	1.00	1.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.00	1.00	0.00	0.00	1.00	0.00
Interchange Working Organ	1.00	1.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.00	1.00	1.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00
Modularize	1.00	1.00	0.50	1.00	0.30	0.30	0.60	0.60	0.30	0.00	0.10	1.00	0.90	0.00	1.00	0.70	0.70	0.10	0.90	0.40	0.30	0.10	0.10
Nest	1.00	1.00	0.71	1.00	0.18	0.47	0.65	0.65	0.24	0.00	0.06	0.53	1.00	0.06	1.00	0.65	0.76	0.06	1.00	0.29	0.35	0.12	0.00
Roll/Wrap/Coil	1.00	1.00	0.50	1.00	0.50	0.50	0.00	0.00	0.00	0.50	0.00	0.00	0.50	1.00	1.00	1.00	1.00	0.00	1.00	0.00	0.50	1.00	0.00
Segment	1.00	1.00	0.68	1.00	0.26	0.42	0.58	0.58	0.21	0.05	0.05	0.53	0.89	0.11	1.00	0.68	0.79	0.05	0.95	0.32	0.37	0.16	0.05
Share Core Structure	1.00	1.00	0.62	1.00	0.38	0.46	0.62	0.54	0.23	0.08	0.08	0.54	0.85	0.15	1.00	1.00	0.85	0.08	0.92	0.23	0.46	0.23	0.08
Share Functions	1.00	1.00	0.67	1.00	0.33	0.47	0.67	0.73	0.27	0.07	0.00	0.47	0.87	0.13	1.00	0.73	1.00	0.00	0.93	0.20	0.40	0.20	0.07
Share Power Transmission	1.00	1.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.00	1.00	1.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00
Shell	1.00	1.00	0.67	1.00	0.22	0.44	0.61	0.61	0.22	0.06	0.06	0.50	0.94	0.11	1.00	0.67	0.78	0.06	1.00	0.28	0.33	0.17	0.00
Telescope	1.00	1.00	0.83	1.00	0.17	0.17	0.00	0.17	0.00	0.00	0.17	0.67	0.83	0.00	1.00	0.50	0.50	0.17	0.83	1.00	0.33	0.00	0.17
Utilize Composite	1.00	1.00	0.86	1.00	0.43	0.57	0.57	0.57	0.00	0.00	0.00	0.43	0.86	0.14	1.00	0.86	0.86	0.00	0.86	0.29	1.00	0.14	0.14
Utilize Flexible Material	1.00	1.00	0.33	1.00	0.33	0.67	0.33	0.33	0.33	0.33	0.00	0.33	0.67	0.67	1.00	1.00	1.00	0.00	1.00	0.00	0.33	1.00	0.00
Utilze Generic Connections	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	1.00	1.00	0.00	0.00	1.00	1.00	0.00	1.00

0 - 25 %	(white)
25 - 50 %	(yellow)
50 - 75 %	(green)
50 - 100 %	(blue)