Transformation Design Theory: A Meta-Analogical Framework

Jason Weaver
e-mail: jasonweaver@mail.utexas.edu

Kristin Wood

Richard Crawford

Department of Mechanical Engineering,
The University of Texas at Austin,
Austin, TX 78712

Dan Jensen
Department of Engineering Mechanics, United States Air Force Academy

Electromechanical products and systems are often designed to transform or reconfigure between two or more states. Each state is customized to fulfill a specific set of functions, and the transformation between these multiple states allows for greater functionality and the elimination of many trade-offs between conflicting needs. Empirical examination of existing transforming systems and their similarities has led to a foundational transformation design theory, with meta-analogies and guidelines that explain how transformation processes occur, when they are useful, and how the designer can ensure their maximum benefit. The foundation of these principles and guidelines forms a meta-analogical framework for designing transformers and transformational systems. This paper presents a history of the development of transformational design theory, including the relationship of the research to case-based reasoning in other fields. Ideation methods are presented that specifically exploit the meta-analogies, i.e., categories of transformers. An example design problem is considered to illustrate the potential utility of this design-by-analogy approach. [DOI: 10.1115/1.3470028]

1 Introduction

Designers of new products or systems today face fierce challenges and competition in the effort to create something that is safe, novel, effective, and that people will actually purchase and use. A successful product must fulfill the needs of the customer in a way that it exceeds that of the competitors. One approach that is often used is the inclusion of more functionality in the system. Multifunction capability, where more than one primary function is exhibited, is becoming the norm, especially within the domain of electromechanical systems. However, casual insertion of more and more functionality can easily lead to feature creep, ineffective user interfaces, high cost, low quality, and low reliability. The careful design of *transformation* into the system can help enable it to fulfill the differing function sets without compromising other customer needs or becoming unwieldy.

To begin, we must first define what we mean by transformation in this context. Transformation is the act of changing state in order to facilitate new functionality or enhance existing functionality [1–3]. Here, a state is defined as a specific physical configuration in which a system performs a function. Transformers differ from single-state multifunction systems in the way these functions are accomplished. A single-state system may fulfill the functions concurrently without physically rearranging its components. This is often accomplished by simply concatenating modules for each function (which can lead to wasted space and weight, as well as increased cost and usability concerns) or by compromising between conflicting functions in order to meet them "well enough." Transformers, on the other hand, focus on each function set independently and at different times, while moving smoothly between states as needed. Some example transformers are included in Fig. 1.

The transformers in Fig. 1 each exhibit multiple distinct states. Each state is focused on a separate set of functions, with the geometry, materials, and kinematics of the system structured in a way that both accomplishes the needed functions and allows for smooth transformation between states. For clarity, their states are listed below:

a. Transformer toy—transforms from toy vehicle to toy robot
b. Inflatable satellite—transforms from compact storage to deployed satellite
c. 6-in-1 screwdriver—transforms between six states, each with a different head
d. V-22 Osprey—transforms from helicopter to airplane (also has a compact storage state)

By using transformation, each of these systems accomplishes functionality that would be almost impossible in a single-state solution. For example, the transformer toy cannot both be an automobile and a humanoid robot; concurrently, the inflatable satellite would not be able to be launched into space in its deployed state, the 6-in-1 screwdriver would be difficult to wield with six simultaneously exposed heads, and the Osprey would not be able to function as both a fixed wing and rotary airfoil simultaneously [4–6].

In this paper, we present a transformation design theory for such systems, as illustrated in Fig. 1. The emphasis of this paper is on understanding the theory as a meta-analogical framework consisting of design principles and guidelines and employing this framework as part of ideation methods. Meta-analogies within the context of this theory are categories or supersets of analogies that represent or distinguish systems with multiple functional states. These meta-analogies provide a basis for performing design-by-analogy to create large, diverse, and innovative solution sets to design problems.

2 Motivation for Research

Using transformation in product design can lead to several advantages. One of the most basic advantages is the improved use of space and material through function sharing and the ability to change geometry. A single, transforming system can often be smaller and lighter than the equivalent single-state device or set of single-function devices. Transformation also leads to the possibility of creating states exclusively for compact storage or portability. A second advantage is the increase in flexibility and convenience that comes from being able to switch between states. For example, the V-22 Osprey (Fig. 1(*d*)) is an aircraft capable of both horizontal and vertical flight via the rotation of its two engines. Military operations may require one capability or the other, depending on the mission; many missions even benefit from both. Where before, a division may need a fleet of both helicopters and

Contributed by the AI/Knowledge Based Systems Committee of ASME for publication in the Journal of Computing and Information Science in Engineering. Manuscript received August 1, 2009; final manuscript received June 30, 2010; published online September 13, 2010. Guest Editors: Ashok K. Goel and Andrés Gómez de Silva Garza.

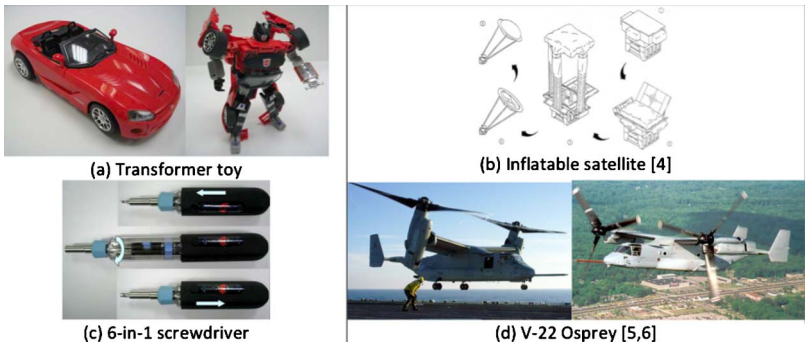


Fig. 1 Examples of transformer products and systems with multiple states

airplanes, the V-22 may be able to replace certain vehicles, thereby conserving space, decreasing training and maintenance costs, and increasing mission capability.

Transformation does have potential drawbacks as well. Some transformers may be complicated to use, while others may be far more expensive than the single-purpose devices they are meant to replace. Because of the possible complexity of the system, design of transformers may be more involved and expensive than simpler products. These drawbacks are largely a function of the design process, thus a designer interested in incorporating transformation would benefit greatly from a formal theory and methodology for designing transformers. Despite this, most transformers are designed with general purpose methodologies, with the transformation process designed ad hoc based on what instinctually seems to work well.

One problem often considered in developing design methodologies is that of representation. Representation is "a physical or mental construct that stands for some other physical or mental construct" [7]. In other words, it is an alternate way of thinking about or communicating a complex, multifaceted system. Means of representation can be specific and concrete, such as a photograph or detailed blueprint, or it could be more abstract, such as a set of customer needs or a comparison to analogous systems. By identifying a classification structure for representing transforming systems, we can begin to compare them and recognize rules and trends for transformation common across the design space.

Our approach in developing a transformation design theory is the empirical analysis of existing and historical transformer systems for the purpose of extracting and formalizing rules and trends within the context of the cognitive science of design (i.e., design-by-analogy) to provide methods and tools to facilitate the design of transforming systems. This approach allows designers to focus on how to actually use the transformation to maximize the competitive edge of the product.

3 Relationship to Prior Research

The development of transformation design theory bears many similarities to two other lines of research: representation systems such as theory of inventive problem solving (TIPS) principles or functional analysis and automated design tools classified as case-based reasoning or design. Both of these paradigms lend themselves naturally to the use of analogies in design.

The meta-analogies for transforming systems described in this paper are similar in structure to the 40 principles outlined as a part of the TIPS methodology [8]. In TIPS, over 2×10^6 patents were analyzed and the resulting information was used to propose a set of 40 principles—tools or ideas that can be used to solve engineering problems or contradictions. For example, a system that needs to increase its speed without increasing its required power could be designed using TIPS principle 19: periodic action. In the same way, the meta-analogies gathered through the research on transforming systems convey a set of ideas or processes for accomplishing transformation that are frequently used in actual design of such systems.

Functional decomposition [9,10], the function-behavior-structure framework [11,12], and other function-based representations [13] also influence the paradigm used in transformation design theory. These representation techniques analyze a complex system as a set of distinct, connected functions. For example, the idea of a "flashlight" may bring to mind images of many specific products, but the idea could be represented fairly well by functions such as "import electrical energy," "convert electrical energy into light," and "direct or focus light." Each key function can often then be traced back to specific physical components in the product's structure, which is what is actually designed and manufactured. In the same way, the meta-analogies described in transformation design theory offer a generalized way of identifying the traits and processes that enable transformation, which the designer can then use to map out the needed structure of the transforming system.

As described in Sec. 4, the development of transformation design theory included the analysis and categorization of a large number of example products. This framework is similar to the idea of case-based reasoning or design [14,15]. Case-based reasoning maintains that it is difficult to completely describe a complex idea in a closed, finite representation. Instead, it may sometimes be more useful to show examples that fit a certain classification than to focus on the classification itself. For example, the functions describing the flashlight above do a good job communicating what a flashlight essentially is, but they do not completely constrain the boundary between what is and is not a flashlight. A clear boundary may be hard to define or even nonexistent, but comparing a set of products that are clearly flashlights and a set that clearly are not can still effectively communicate the idea. Future design of a flashlight, then, could use the assembled set of flashlights as analogies and benchmarks to identify what the design needs to fulfill. A repository of many individual cases can be searched and analyzed to gather useful analogous products for any system needing design [14–16]. Similarly, the assembled repository of transforming systems described in Sec. 6 can be used as an automated database search to assemble not only data on useful meta-analogies describing transformation but the analogous systems themselves.

4 Development of Transformation Design Theory

Transformation design theory was developed through an approach of both induction and deduction. This approach is shown in Fig. 2. The inductive component of this approach is an empirical study of existing transformers. Each transforming system is deconstructed to identify specific functions, properties, characteristics, and processes related to transformation. These are distilled into a set of well-defined principles or guidelines describing various aspects of the transformation process. The complementary

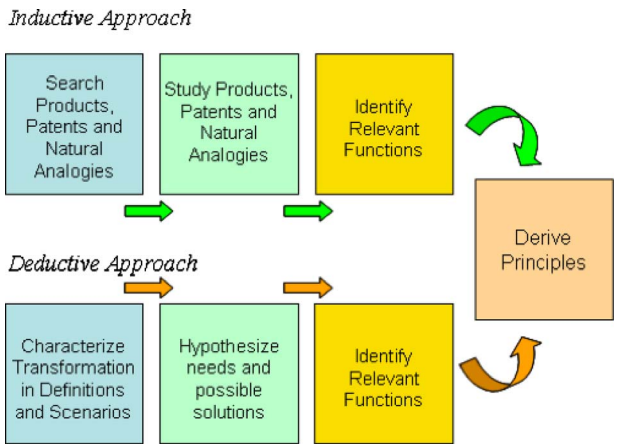


Fig. 2 Research approach for transformation design theory

deductive component of the research approach begins with possible design scenarios where transformation may be useful. The principles and guidelines previously developed are used to generate solutions, which are then analyzed to refine the definitions.

4.1 Patent Search. For several years, we have studied the transformation process by examining existing products, patents, and biological examples. The first stage of research studied 35 patents for transforming devices [1,17,18]. These were found by searching databases for key terms such as "transform" and "reconfigure." The methodology for identifying the patents is illustrated in Fig. 3. Dissection of the summaries, preferred embodiments, and illustrations revealed a set of 19 descriptive meta-analogies. These were divided into a set of three "transformation principles" and 16 "transformation facilitators," where the principles describe the general form of the transformation (e.g., expanding/collapsing to change state) and the facilitators describe the supporting functions and characteristics enabling the transformation (e.g., inflating or unfolding). The discovery of each new principle or facilitator was tracked and examination of patents continued until an appreciable number revealed no new meta-analogies (Fig. 4). Although not a rigorous proof of completeness, this initial study was sufficient to reveal information describing a large number of transformation processes.

4.2 Natural Analogies. A second stage of research studied a set of approximately 50 additional patents and 40 natural analogies (plants and animals) [19]. These natural analogies were identified through literature review, keyword searches, and interviews with biologists and other professionals, as shown in Fig. 5. This stage discovered an additional three facilitators, giving a total of 19. Definitions of these facilitators were later refined slightly during the deductive approach, creating a new set with 20 total facilitators [20].

4.3 Existing Products. The third empirical study revisited many of the patents and natural analogies previously studied, and added approximately 100 products actually existing in the market [20–22]. These products were discovered partially through the methods shown for patents and natural analogies, and partially through individual experience, Internet searches, advertisements, stores, and catalogs. A methodology for this product search is shown in Fig. 6.

This third study confirmed that the existing set of three principles and 20 facilitators was sufficient to describe all 190 transforming systems analyzed. This stage of research also examined closely the relationships among the various principles and facilitators, which is described in more detail in Sec. 6

4.4 Deductive Methods. While the three stages of inductive research were being conducted, we also examined transformation

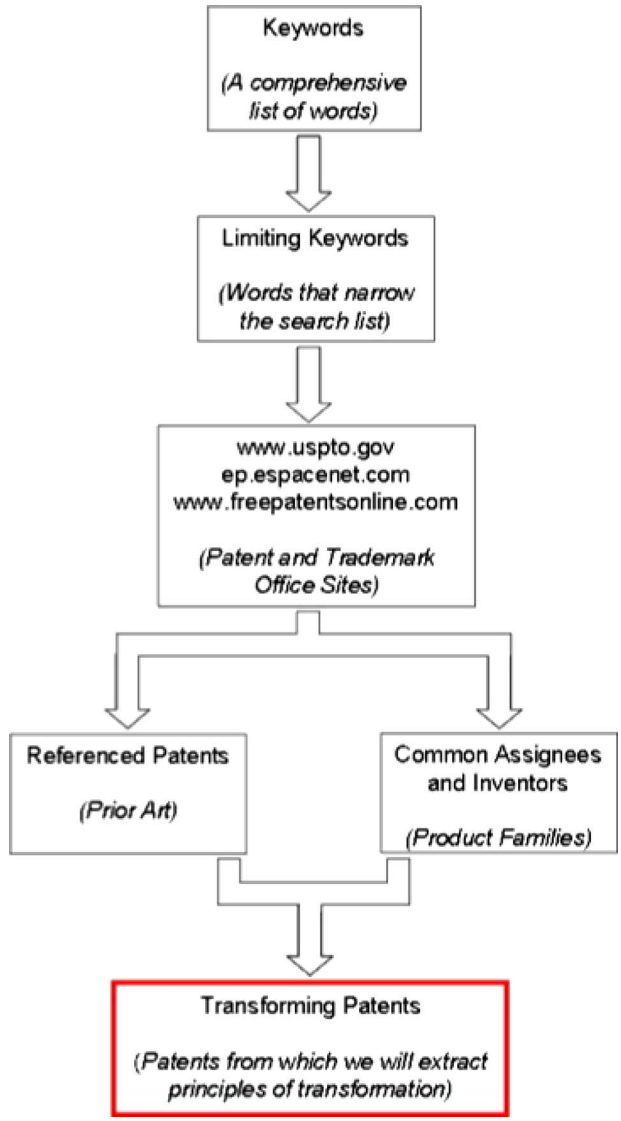


Fig. 3 Search methodology for patented devices exhibiting transformation

design theory from a deductive standpoint. The definitions of the principles and facilitators were examined to try to eliminate confusion or overlap in their scope. These principles and facilitators were also studied from kinematic, topological, and linguistic

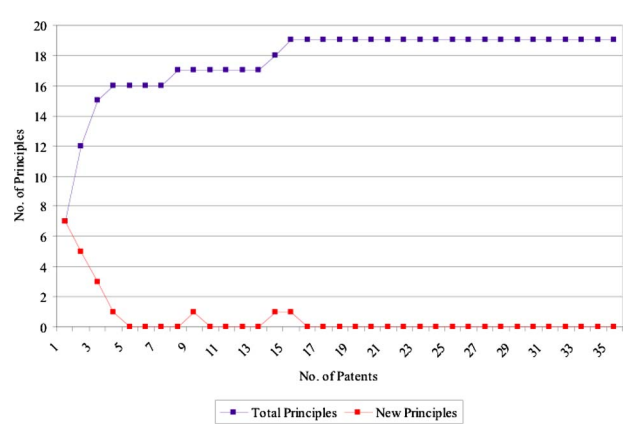


Fig. 4 Identification of new principles and facilitators from patents in initial study [1]

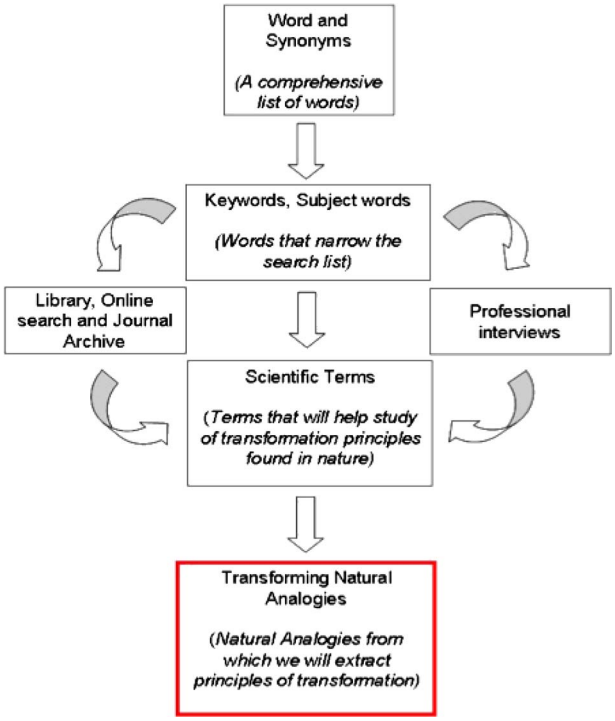


Fig. 5 Search methodology for natural analogies exhibiting transformation

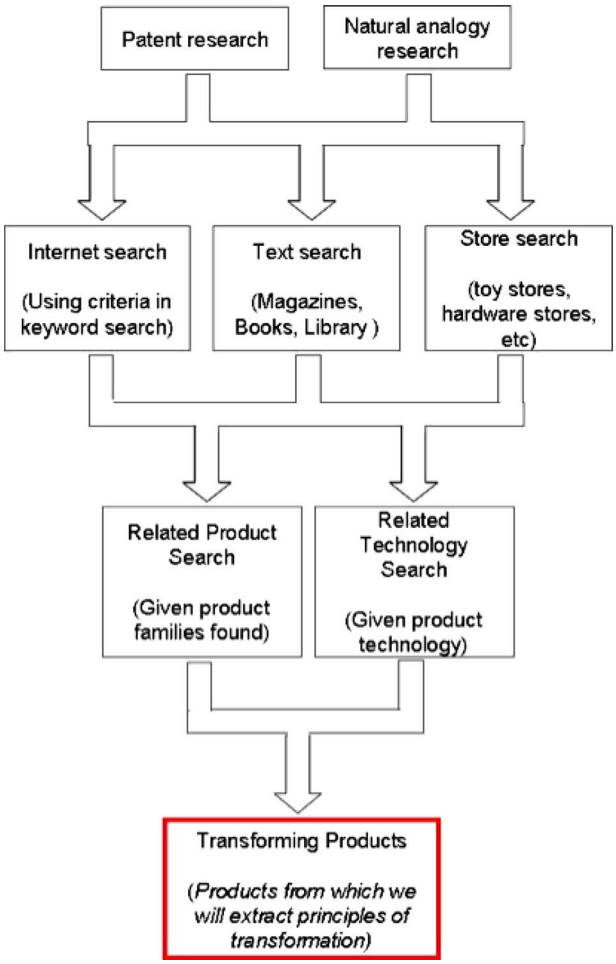


Fig. 6 Search methodology for existing transforming products

points of view to determine how and why they go together and what alternate ways to classify the transformation processes may exist. We also examined the question of *when* transformation is useful, which led to several situations where transformation is particularly fitting. Three key indicators were proposed to identify such situations [3,22].

Several sample design problems have also been used to test transformation design theory [1–3,17–23]. In each case, a hypothetical scenario was presented that could benefit from transformation. The existing set of transformation principles and facilitators were used to create solutions to the problem. These exemplar solutions were then analyzed to see how useful the principles and facilitators are in design, how thoroughly they can describe transformation, and any shortcomings that could be overcome by further refinement. An example of transformation design theory being used in design is described in Sec. 7

5 Transformation as Meta-Analogies

We now introduce transformation indicators, principles, and facilitators identified through this research. Transformation design theory proposes that all transforming mechanical systems can be accurately described by a set of transformation meta-analogies. *Transformation indicators* describe three types of situation where transformation is appropriate. *Transformation principles* list the three general forms of transformation. *Transformation facilitators* describe the various supporting features that aid transformation processes.

5.1 Transformation Indicators. There are three general indicators that a system may benefit from transformation.

1. *Packaging*. The system needs to be packaged for portability, storage, deployment, and/or protection. As an example, the inflating satellite in Fig. 1(*b*) is stored in a compact state for transport into orbit, and then deploys into an expanded state when in position.
2. *Related processes*. The customer requires multiple sets of related processes or functions, which would be more convenient if combined in a single system. A necessary condition for this indicator is that the processes must be asynchronous, that is, performed at different times. For example, the 6-in-1 screwdriver in Fig. 1(*c*) combines the closely related but asynchronous processes for screwing six different sizes and shapes of screw heads (slotted, Philips, and star).
3. *Common flow*. There exists multiple sets of functions that may be unrelated but share a common flow of energy or material that can be shared between states in a single system. The V-22 Osprey in Fig. 1(*d*) exhibits this indicator, as the two states share the flows of power to the engines, air through the engines and over control surfaces, and signals from the pilot to the engine and control surfaces.

5.2 Transformation Principles. A transformation principle is defined as a generalized directive to bring about a certain type of mechanical transformation [22]. Transformer principles are formulated as pairs of active verbs. All general forms of mechanical transformation are thought to fall under at least one of three principles.

1. *Expand/collapse*—Change physical dimensions of an object to bring about an increase or decrease in occupied volume primarily along an axis, in a plane, or in three dimensions.
2. *Expose/cover*—Reveal or conceal a new surface to alter functionality.
3. *Fuse/divide*—Make a single functional device become two or more devices or vice versa where at least one of the

(*a*) (*b*) (*c*)

Fig. 7 (*a*) Expand/collapse [24], (*b*) expose/cover [25], and (*c*) fuse/divide [26]

multiple devices has a distinct functionality separate from the function of the single device.

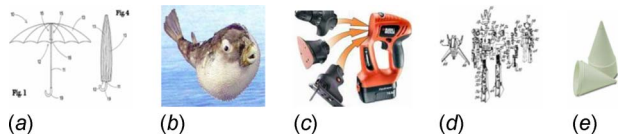
Exemplar products for each principle are shown in Fig. 7.

5.3 Transformation Facilitators. A transformation facilitator is defined as a design construct that helps or aids in creating mechanical transformation. It describes the underlying characteristics or processes that facilitate transformation, but it is not capable of creating transformation outside of an overarching principle. For example, one facilitator is *modularize*. Introducing modularity into a system will often greatly help a transformation process. However, the mere fact that a system is composed of modules is insufficient to produce transformation. Instead, transformation occurs as these modules are changed or physically rearranged as described by one or more of the transformation principles. There are currently 20 distinct facilitators.

1. *Conform with structural interfaces*. Statically or dynamically constrain the motion of a component using structural interfaces. This facilitator is widespread throughout the design space. Parts or interfaces are held in place or released, often by fasteners, friction, or interference with other interfaces.
2. *Enclose*. Manipulate object in three dimensions in order to enclose a three-dimensional space. Enclose, fan, and translate are related, describing the ability to change dimensions in three, two, or one dimension, respectively. Enclose also involves using this change in dimension to surround a space in a new way and to accomplish a new function.
3. *Fan*. Manipulate object in two dimensions to create an elongation, planar spread, or enclosed space to alter its function.
4. *Flip*. Perform different functions based on the orientation of the object.
5. *Fold*. Create relative motion between parts or surfaces by hinging, bending, or creasing (see Fig. 8).
6. *Furcate*. Change between two or more discrete and stable states determined by the boundary conditions. This facilitator relates to how the transformation process is actuated, using springs, bistable materials, or other means to "pop" from one stable state, through an unstable transition, and into another stable state.
7. *Inflate*. Fill an enclosed space, constructed of flexible material, with fluid media to change geometry and function.
8. *Interchange working organ*. Interchange working organ to produce a different end effect. "Working organ" is a term derived from Altshuller's laws of technical system evolution [8]. It can also be described as the "work piece" or "end effector."

(*a*) (*b*) (*c*) (*d*) (*e*)

Fig. 8 (*a*) Conform with struct. interfaces [27], (*b*) enclose [28], (*c*) fan [29], (*d*) flip [30], and (*e*) fold [31]



(*a*) (*b*) (*c*) (*d*) (*e*)

Fig. 9 (*a*) Furcate [32], (*b*) inflate [33], (*c*) interchange working organ [26], (*d*) modularize [34], and (*e*) nest [35]

9. *Modularize*. Localize related functions into product modules.
10. *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 (see Fig. 9).
11. *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.
12. *Segment*. Divide single contiguous part into two or more parts.
13. *Share core structure*. Device's core structure remains the same while the periphery reconfigures to alter the function of the device.
14. *Share functions*. Perform two or more discrete functions. This could entail typical function sharing, where one component performs two functions at the same time, or function *shifting*, where one component performs two functions at separate times while in the different states.
15. *Share power transmission*. Transmit power from a common source to perform different functions in different configurations (see Fig. 10).
16. *Shell*. Embed an element in a device where the element performs a different function. This differs from nest, in part, in that shell is not geometry-dependent, i.e., the inner component is not required to conform closely with the geometry of the outer enclosure.
17. *Telescope*. Manipulate an object along an axis to create elongation, planar spread, or enclosure to alter its function.
18. *Utilize composite*. Form a functional part from two or more nonfunctional parts.
19. *Utilize flexible material*. Change object dimensions with change in boundary conditions.
20. *Utilize generic connections*. Employ internal or external connections (structural and power) that can be used by different modules to perform different functions or perform the same function in a different way. (see Fig. 11).

(*a*) (*b*) (*c*) (*d*) (*e*)

Fig. 10 (*a*) Roll/wrap/coil [36], (*b*) segment [37], (*c*) share core structure [38], (*d*) share functions [39], and (*e*) share power transmission [40]

(*a*) (*b*) (*c*) (*d*) (*e*)

Fig. 11 (*a*) Shell [41], (*b*) telescope [42], (*c*) utilize composite [43], (*d*) utilize flexible material [44], and (*e*) utilize generic connections [45]

Table 1 Portion of Transformer Repository (Transposed)

Transformer example	VTOL aircraft (V-22 Osprey)	6-in-1 screwdriver
Source	http://en.wikipedia.org/V-22	Found in Sears
Expand/collapse	0	0
Expose/cover	1	1
Fuse/divide	0	1
Conform w/structural interfaces	1	1
Enclose	0	0
Fan	0	0
Flip	1	1
Fold	1	0
Furcate	0	0
Inflate	0	0
Interchange working organ	0	1
Modularize	1	1
Nest	0	1
Roll/wrap/coil	0	0
Segment	1	1
Share core structure	1	1
Share function	1	1
Share power transmission	1	1
Shell	0	1
Telescope	0	1
Utilize composite	0	0
Utilize flexible material	0	0
Utilize generic connections	0	1

6 Correlations Among Transformation Meta-Analogies

As mentioned previously, the third stage of inductive research compiled a list of 190 transforming systems [20,22]. Where the purpose of the prior studies had been primarily to identify and define the set of principles and facilitators, the main goal of this empirical study was to examine how the different principles and facilitators work together in typical products to produce a transformation process.

6.1 Transformer Repository. To aid in the analysis of transformation in general, a repository of existing transformers was formed with the following information entered for each transformer:

- name
- picture
- source
- how it was discovered
- number of states
- whether one of the states is a storage state
- domain (furniture, tool, and vehicle)
- what principles and facilitators are present

The presence of principles and facilitators was recorded by forming a matrix on the spreadsheet, with transforming products along the rows and principles/facilitators along the columns. If a certain principle or facilitator is found in a transformer, the cell intersecting that column and row received a "1," otherwise it received a "0." A small part of this transformer repository is reproduced in Table 1.

6.2 Vector Space Analysis of Transformer Repository. To determine how the principles and facilitators are distributed throughout the design space, we formed a square, symmetric matrix by multiplying the transformer repository by its transpose, as illustrated in Fig. 12. This matrix has the principles and facilitators along both the rows and columns. Each diagonal entry (e.g., row A, column A) is the total number of products using a given meta-analogy (facilitator A) in the repository. Off-diagonal entries (e.g., row A, column B) show how many times the two meta-analogies (facilitator A and facilitator B) occur together in observed products. This matrix is referred to as the princple-facilitator (PF) matrix and is actually composed of four submatrices: linking (1) principles with principles, (2) principles with facilitators, (3) facilitators with principles, and (4) facilitators with facilitators. The PF matrix is included in Appendix A.

In addition to this original PF matrix, a modified PF matrix was also presented (Appendix B). In this matrix, each row is normalized by the total number of products of the row meta-analogy. The formula used is

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

The modified PF matrix is now asymmetric, with diagonal values of 1. Each off-diagonal term is now a percentage. The intersection of row A and column B shows the percentage of products using facilitator A that also use facilitator B. The related entry at

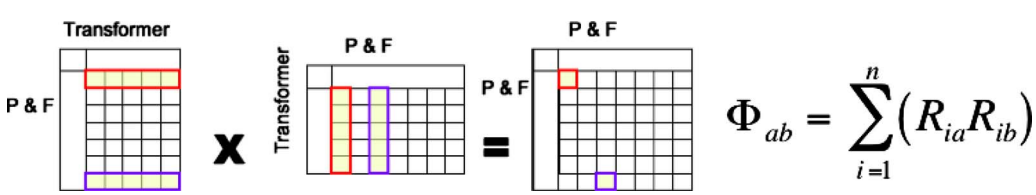


Fig. 12 Assembly of PF matrix from transformer repository data

Table 2 Notable correlations between principles and facilitators

	Expand/collapse	Expose/cover	Fuse/divide
Most prevalent	1. Conform w/struct. interfaces 2. Nest 3. Shell	1. Shell 2. Share functions 3. Flip	1. Segment 2. Conform w/struct. interfaces 3. Modularize
Least prevalent	1. Interchange working organ 2. Utilize generic connections 3. Share power transmission	1. Inflate 2. Utilize generic connections 3. Furcate	1. Inflate 2. Fan 3. Furcate

row B and column A shows the percentage of products using facilitator B that also include facilitator A. The two values may be very different, depending on the relative scope of the two meta-analogies examined. For example, the modified PF matrix in Appendix B shows that the intersection for row "Inflate" and column "Shell" has a value of 0.67, meaning that 67% of inflating transformers is also shell. This high percentage seems logical since the inflating process often entails placing the fluid media inside a flexible and hollow shell. The opposite intersection, between row "Shell" and column "Inflate" has the much lower value of 0.05, meaning that only 5% of all shelling transformers also involve an inflation process. This result also appears generally correct, as there are many types of transformation that require the concept of shelling, but are totally unrelated to inflation.

6.3 Correlations Among Transformation Meta-Analogies. Using these results, we were able to quantify what previously had been hypothesized by intuition: that there exist consistent, predictable patterns, and trends in how the different principles and facilitators interact. These correlations can be easily summarized by first looking at the interactions between principles, then between principles and facilitators, and then finally among the various facilitators.

6.3.1 Principle-Principles Correlations. Inspection of the original PF matrix (Appendix A) reveals that the most common principle is *Expose/cover*, with 160 out of 190 examples exhibiting this mode of transformation. The most frequent pairing occurs between Expose/cover and *Expand/collapse*, with 117 examples showing both principles together. The principle *Fuse/divide* seems to be more used singly, as it was less likely to be found in conjunction with one of the other principles.

6.3.2 Principle-Facilitator Correlations. The PF matrix has two submatrices relating principles and facilitators: one down the left side and one across the top. In the modified PF matrix, these two sections reveal different aspects of how the meta-analogies interact. In the submatrix across the top, each value tells the percentage of examples exhibiting a certain principle that also make use of a certain facilitator. It shows how commonly the facilitator occurs under the principle. For example, the facilitator *Inflate* has a value of 0.12 for Expand/collapse, 0.01 for Expose/cover, and 0.00 for Fuse/divide. This shows that the facilitator is fairly uncommon overall. Even with Expand/collapse, the principle with the highest value, Inflate only occurs in 12% of the examples.

In the submatrix down the left side, a given location will tell the percentage of examples with a certain facilitator that also employ the given principle. In other words, it shows how exclusively a facilitator is linked to a principle. Using the same pairing as before, we see that this submatrix gives values of Inflate with Expand/collapse at 0.89, with Expose/cover at 0.11, and with Fuse/divide at 0.00. This matches the overall impression from the other submatrix that Expand/collapse is the biggest contributor to Inflate. In fact, 89% of the inflating processes in the repository were exclusively linked to Expand/collapse-based transformations.

From these data, we can easily determine which facilitators consistently link to certain principles. Many facilitators are largely principle independent, but some show strong correlation with or against one or more principles. These results are summarized in Table 2.

6.3.3 Facilitator-Facilitator Correlations. The portion of the PF matrix linking facilitators to other facilitators is large and complex enough that it is difficult to identify all the useful information in a glance. However, it does contain the same two data points as described above for every combination of two facilitators. To simplify the information and bring out relevant outliers, a "Facilitator Correlation Index" can be constructed (Appendix C). Examining the two data points for each facilitator pair could reveal one of the following trends.

- Both values are high, meaning that there is a high likelihood of the facilitators always appearing together (high mutual correlation).
- One value is high and one is low, meaning that one may be dependent on the other or may be more limited in scope (high one-way correlation).
- Both values are low, meaning that the two facilitators seem to be exclusive of each other, either through incompatibility or simple lack of common purpose (low mutual correlation).
- Both values are average, showing occasional co-existence but no exceptional correlation.

These trends are shown graphically in the Facilitator Correlation Index with a check mark for high mutual correlation, an arrow for a one-way correlation, and an X for a low correlation. From this chart, a designer can look at the row of any facilitator of interest and instantly tell what other facilitators to consider including to create a complete, elegant transformation. He can also consciously choose to go against these typical correlations to create new solutions that are novel and unconventional. Thus, an understanding of transformation design theory will allow the designer to better understand how transformation works and how its power can be effectively harnessed to solve the problem at hand.

7 Ideation Methods in Transformer Design

As research into transformation has continued, a primary focus has been how this information can be practically used in engineering design. Several techniques have been developed that incorporate components of transformation design theory into the design method, particularly at the stage of concept generation. Because of the meta-analogical framework inherent to transformation design theory, these techniques can turn conventional concept generation (CG) methods into design-by-analogy methods through the re-representation of the problem. Initial testing of many of

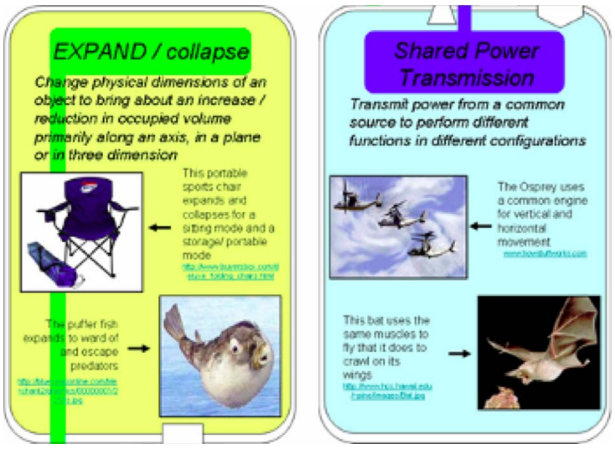


Fig. 13 T-Cards for a transformation principle and facilitator

these techniques indicates that their use leads to more expansive coverage of the design space than general-purpose CG methods alone [46,47].

7.1 Modified Mind-Maps. One of the more basic methods involves the conventional mind-mapping technique [2]. Mind-mapping is commonly used to organize brainstorming results by categorizing and linking ideas from general to specific in a web-like structure. Transformation meta-analogies may be used in mind-mapping by using the three principles as initial categories, and then using the facilitators as subcategories branching out to the specific solutions.

7.2 T-Cards. A second concept generation method involves the use of "T-cards" [3]. These are essentially color-coded index cards illustrating the different transformation meta-analogies. Principles are described with yellow cards, and facilitators appear on blue cards. Each card gives the definition for the meta-analogy, along with two pictures of exemplar products and a brief explanation of how they use the meta-analogy. In addition, colored stripes and other visual cues link principles and facilitators that often occur together. The designer can use the cards individually as references or assemble them in chains to build complete transformation processes. Two T-cards are shown in Fig. 13.

7.3 WordTrees. A third method uses transformation meta-analogies in conjunction with a thesauruslike database called WordNet [48,49]. In WordNet, the user inputs a key term, such as a principle, facilitator, function, or customer need. The database returns a list of related words. These are organized into *troponyms* (more specific subtypes of the key word), *hypernyms* (more general terms that include the key word), and *sister terms* (words that share a common hypernym with the key word). Use of the database, which seeks to organize as much of the English language as possible, often leads the designer into domains and vocabulary far removed from the original problem. These far-field analogies bring additional insight and can increase the design space far beyond what the designer would discover independently. For more information on this method, the reader is referred to literature [20,47,50–52].

7.4 Case-Based Automated Design. In addition to using the meta-analogies (principles, facilitators, and indicators) to guide design, the designer can also make use of specific systems and products analogous to the task at hand. The transformer repository studied in Sec. 6 can be used to create a partly automated analogy search. This repository can easily be sorted to discover, which previously identified systems bear similarities to the design problem. These similarities can be based on any information recorded in the repository, such as specific physical characteristics, number or types of primary functions, general domains, or required processes or constraints in the transformation. Once the relevant transforming systems have been identified and sorted, this information can be applied to the design process in two ways.

First, the repository yields a wealth of actual working products that are analogous to the design problem and can be used as starting points or references as the new system is designed. Second, the calculations described in Sec. 6 can also be run on only this subset of the repository. This will identify the specific principle and facilitator combinations that are often successfully used in transformers of this type. The designer can then seek a solution with similar processes and characteristics to the observed systems. This process can be electronically automated and is very similar to case-based reasoning, as described in Sec. 3. Previous solutions are automatically retrieved for reference in the design problem, the designer uses the previous designs as starting points for the new problem, and the resulting solutions can be added to the repository for future use in other design problems.

7.5 Example Design Problem. To illustrate the possible use of transformation design theory in the design of reconfigurable systems, we examine an example design problem. Consider the interior furniture and fixtures in a recreational vehicle. Many recreational vehicles (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 domain (*structure/furniture*), and by 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. 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 specific products for inspiration and implantation of design-by-analogy techniques.

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. 14.

Fig. 14 "Flight" convertible shower/bath/wash table [53]

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, usable transformer.

8 Conclusion

The field of transformation design theory is relatively new but is rapidly growing. As flexible and reconfigurable systems become increasingly popular in design, a deeper understanding of transformation processes and how to use them becomes more important. Transformation design theory uses a meta-analogical framework to represent transforming systems in terms of when transformation is appropriate (indicators), what avenues of transformation are available (principles), and how to construct transformation processes effectively (facilitators). The use of these meta-analogies across the design space is consistent and occurs in predictable combinations. Several concept generation techniques have been developed that make use of transformation meta-analogies to discover useful analogies from nature, existing products, the designer's experience, relationships in terminology, and fundamental correlations between the meta-analogies themselves. These techniques have been shown to produce innovative, functional solutions, with transformation processes that help deliver multifunction capability in an efficient, compact package.

Acknowledgment

The authors would like to acknowledge the support provided by the Cullen Endowed Professorship in Engineering, University of Texas at Austin, the National Science Foundation under Grant No. CMMI-0555851, 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.

Appendix A: Original 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	**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 %	
25 - 50 %	
50 - 75 %	
50 - 100 %	

Appendix B: Modified 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**	0.00	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 %	
25 - 50 %	
50 - 75 %	
50 - 100 %	

Appendix C: Facilitator Correlation 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.						✔				✔	✔		✔	✔	✔		✔				
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		↗		x	↗			↗			↗	x
Interchange Working Organ	↗	x	x		x	x	x		↗		x		↗	↗	↗	✔	↗	x	x	x	✔
Modularize	✔			✔									✔	✔	✔		✔				
Nest	✔				✔								✔				✔				
Roll/Wrap/Coil									x							x	↗			✔	
Segment	✔					✔		x		✔	✔			✔	✔		✔				
Share Core Structure	✔									✔			✔		✔		✔				
Share Functions	✔			✔	✔					✔			✔				✔				
Share Power Transmission	↗	x				x		✔	↗		x		↗	↗	↗		↗			x	
Shell	✔				✔				✔	✔			✔	✔	✔						
Telescope			x			x		x		↗			↗				↗				x
Utilize Composite	↗							x					↗				↗				
Utilize Flexible Material								x		↗	✔					x	↗			x	
Utilze Generic Connections	↗	x	x	x	x	x	x	✔	↗				↗	↗	↗			x		x	

Mutual High Correlation	✔
High One-Way Correlation	↗
Mutual Low Correlation	x

Correlation over 75%	
Correlation over 50%	
Correlation below 10%	

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," International Design Engineering Technical Conferences, Philadelphia, PA, Paper No. DETC-2006-99575.

[2] Skiles, S. M., Singh, V., Krager, J. E., Seepersad, C. C., Wood, K. L., and Jensen, D., 2006, "Adapted Concept Generation and Computational Techniques for the Application of a Transformer Design Theory," International Design Engineering Technical Conferences, Philadelphia, PA, Paper No. DETC-2006-99584.

[3] Singh, V., Walther, B., Krager, J., Putnam, N., Koraishy, B., Wood, K. L., and Jensen, D., 2007, "Design for Transformation: Theory, Method, and Application," International Design Engineering Technical Conferences, Las Vegas, NV, Paper No. DETC-2007-34876.

[4] Freeland, R. E., Bilyeu, G. D., Veal, G. R., Steiner, M. D., and Carson, D. E., 1997, *Large Inflatable Deployable Antenna Flight Experiment Results*, 48th Congress of the International Astronautical Federation, Turin, Italy.

[5] Ard, S., 2004, "041208-N-5313A-012," Navy News Service, http://www.navy.mil/view_single.asp?id=19521
[6] Pugh, V., 2002, "V-22 Osprey," Navy News Service, http://www.navy.mil/view_single.asp?id=1673
[7] Linsey, J. S., Wood, K. L., and Markman, A. B., 2008, "Modality and Representation in Analogy," Artif. Intell. Eng. Des. Anal. Manuf., **22**, pp. 85–100.
[8] Altshuller, G. S., 1984, *Creativity as an Exact Science*, Gordon and Breach, Luxembourg.
[9] Stone, R. B., Wood, K. L., and Crawford, R. H., 1999, "Product Architecture Development With Quantitative Functional Models," ASME Paper No. DETC99/DTM-8764.
[10] Hirtz, J., Stone, R. B., McAdams, D. A., Szykman, S., and Wood, K. L., 2002, "A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts," Res. Eng. Des., **13**(2), pp. 65–82.
[11] Gero, J. S., 1990, "Design Prototypes: A Knowledge Representation Schema for Design," AI Mag., **11**(4), pp. 26–36.
[12] Gero, J. S., and Kannengiesser, U., 2004, "The Situated Function-Behaviour-Structure Framework," Des. Stud., **25**(4), pp. 373–391.
[13] Chakrabarti, A., Sarkar, P., Leelavathamma, B., and Nataraju, B. S., 2005, "A Functional Representation for Aiding Biomimetic and Artificial Inspiration of New Ideas," Artif. Intell. Eng. Des. Anal. Manuf., **19**, pp. 113–132.
[14] Watson, I., and Marir, F., 1994, "Case-Based Reasoning: A Review," Knowl. Eng. Rev., **9**, pp. 327–354.
[15] Maher, M. L. and Pu, P., eds., 1997, *Issues and Applications of Case-Based Reasoning in Design*, Lawrence Erlbaum, Mahwah, NJ.
[16] Sriram, D., Stephanopoulos, G., Logcher, R., Gossard, D., Groleau, N., Serrano, D., and Navinchandra, D., 1989, "Knowledge-Based System Applications in Engineering Design: Research at MIT," AI Mag., **10**(3), pp. 79–96.
[17] Singh, V., Warren, L., Putnam, N., Walther, B., Koraishy, B., Wood, K., Becker, P., Danielson, A., Jensen, D., and Szmerekovsky, A., 2006, "A Novel Exploration Into Gust Resistant Operation of MAVs/UAVs Through Transformation," Proceedings of Second U.S.-European Conference on Micro Air Vehicles, Destin.
[18] Skiles, S. M., 2006, "Development of Principles of Facilitators for Transformational Product Design," Mechanical Engineering, University of Texas at Austin, Austin, TX.
[19] Singh, V., 2007, "Design for Transformation: Design Principles and Approach With Concept Generation Tools and Techniques," Mechanical Engineering, University of Texas at Austin, Austin, TX.
[20] Weaver, J., 2008, "Transformer Design: Empirical Studies of Transformation Principles, Facilitators, and Functions," Mechanical Engineering, University of Texas at Austin, Austin, TX.
[21] Putnam, N., 2008, "Energy Systems in MAVs–Theoretical and Applied Perspectives," Mechanical Engineering, University of Texas at Austin, Austin, TX.
[22] Weaver, J., Wood, K. L., and Jensen, D., 2008, "Transformation Facilitators: A Quantitative Analysis of Reconfigurable Products and Their Characteristics," International Design Engineering Technical Conferences, Brooklyn, NY, Paper No. DETC-2008-49891.
[23] Wang, D., Kuhr, R., Kaufman, K., Crawford, R., Wood, K. L., and Jensen, D., 2009, "Empirical Analysis of Transformers in the Development of a Storyboarding Methodology," International Design Engineering Technical Conferences, San Diego, CA, Paper No. DETC-2009-87420.
[24] 2005, "Brute B-2 Folding Chair," http://www.buyersbox.com/deluxe_folding_chairs.html
[25] 2005, "Two-foot Stepping Ladder," http://loopy.cc/pt_stools.php
[26] 2005, "Black & Decker 14.4V Cordless Quattro Multi-Tool With Kit Box," http://www.lenehans.ie/lenehans/Images/DB_Detail/kc2002fk.jpg
[27] Ackeret, P., 2002, "Multipurpose Hand-Held Device," U.S. Patent No. 6,493,893.
[28] 2005, "Cardboard Box," http://www.simply-boxes.co.uk/NewsEngineer.asp
[29] 2005, "Fan," http://en.wikipedia.org
[30] 2006, "Mighty Lights," http://www.solarquest.com/products/lighting/LEDS/MightyLights.jpg
[31] 2006, "Transition Car," http://www.terrafugia.com
[32] Villa, F., 2005, "Umbrella Apparatus," U.S. Patent No. 6,910,490.
[33] 2005, "Puffer Fish," http://blueseasonline.com/Merchant2/graphic/00000001/2258s.jpg
[34] Ogawa, I., 1980, "Articulated Reconfigurable Robot Doll," U.S. Patent No. 4,206,564.
[35] 2005, "Solo Cups®," http://www.summitcoolers.com/images/p_cone4oz.jpg
[36] 2006, "Armadillo," http://magma.nationalgeographic.com/ngexplorer/0503/
[37] "Foldable Ruler," http://hand-tools.hardwarestore.com/21-399-folding-rulers.aspx
[38] 2006, "Blower and Vacuum," http://www.ebigchina.com/ebcps/4/pd/888604.html
[39] 2006, "AmphibiCAR," http://www.w3sh.com/archives/amphibicar-thumb.jpg
[40] 2006, "V-22 Osprey," http://en.wikipedia.org/v-22.html
[41] 2006, "Turtle," http://www.pfmt.org/wildlife/endangered/al_red.htm
[42] Vann, C. S., 2003, "Telescoping Writing Instrument," U.S. Patent No. 6,616,365.
[43] 2005, "Lego Building Blocks LEGO®," http://www.seattlerobotics.org/encoder/200108/Image69.jpg
[44] "Bat," http://www.hcc.hawaii.edu/~pine/images/Bat.jpg
[45] 2005, "Toobeez®," http://www.project-connect.net/toobeez.html
[46] Jensen, D., Weaver, J., Wood, K., Linsey, J., and Wood, J., 2009, "Techniques to Enhance Concept Generation and Develop Creativity," American Society for Engineering Education Annual Conference, Austin, TX, Paper No. AC2009-2369.
[47] Weaver, J. M., Kurh, R., Wang, D., Crawford, R. H., Wood, K. L., Jensen, D., and Linsey, J. S., 2009, "Increasing Innovation in Multi-Function Systems: Evaluation and Experimentation of Two Ideation Methods for Design," International Design Engineering Technical Conferences, San Diego, CA, Paper No. DETC-2009-86256.
[48] "WordNet: A Lexical Database for the English Language," http://wordnetweb.princeton.edu/perl/webwn
[49] Fellbaum, C., 1998, *Wordnet, an Electronic Lexical Database*, MIT, Cambridge, MA.
[50] Linsey, J. S., 2007, "Design-by-Analogy and Representation in Innovative Engineering Concept Generation," Mechanical Engineering, University of Texas at Austin, Austin, TX.
[51] Linsey, J., Wood, K., and Markman, A., 2008, "Increasing Innovation: Presentation and Evaluation of the Wordtree Design-by-Analogy Method," ASME Design Theory and Methodology Conference, New York.
[52] Linsey, J., Wood, K., and Markman, A., 2008, "WordTrees: A Method for Design-by-Analogy," Proceedings of the 2008 ASEE Annual Conference and Exhibition, Pittsburgh, PA.
[53] Hauser, I., 2007, "Flight Supercompact Bathroom," http://www.yankodesign.com/index.php/2007/08/22/supercompact-bathroom