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CONCEPT OPPORTUNITY DIAGRAMS, A VISUAL MODELING METHOD TO FIND MULTIFUNCTIONAL DESIGN CONCEPTS

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ABSTRACT

A transforming product is a system that has different functionality when physically changed or reconfigured into a different state. This increased functionality allows diverse customer needs to be met in a single product. Transforming devices have become more prevalent in recent years, as customers desire both increased capabilities and reduced complexity to reduce waste in our society. When designing a multifunctional product that transforms from one state to another, it can be difficult to conceptualize a design that does not reduce effectiveness or provide a compromise in either state. Transformational Design Theory has been developed and shows basic principles and facilitators that enable transformation to occur within a product space. An illustrative example is a chair designed to flip over to be used as a table. Flip is one of the 19 facilitators that are found in transformation design. This is also an example of expose/cover, a transformation design principle. Certain principles and facilitators are more prevalent than others in different design domains (such as tools, storage, organisms etc.). If we know the states that exist within the transformer, concept opportunity diagrams can be used to determine the opportunities for transformation within each state. When the diagrams are paired with a constituent relationship chart specific to each domain, new design concepts may be facilitated. This technique creates a cognitive process for designers where they process a series of questions when creating the concept opportunity diagram. The diagram will help them understand the unanticipated additional design space of each state. The Constituent Relationship Chart is a tool that allows them to apply their knowledge of these states to the facilitator hierarchy so that prospective facilitators can directly contribute to originally unforeseen design concepts. This paper presents this twofold process known as the Transformer Diagram Matching Method and shows the results on a fully functioning prototype of an office supply transformer. Although the proposed process is detailed, it allows the designer to find a large number of quality concepts they would not have foreseen otherwise. Our original concept generation processes produced thirty eight ideas, but this process added another thirty two ideas to the design space. The paper indicates specifically how this method can be integrated in with the standard transformational design process as well as suggests strategies for implementation within other design techniques.

1. INTRODUCTION

1.1 TRANSFORMATION DESIGN

A transformer is "a system that exhibits a state change in order to facilitate a new functionality or enhance an existing functionality" [1]. Transformers, or reconfigurable devices, often occur in various design industries and range in products from tools, organisms, structures, vehicles and storage [1]. Transforming products have become much more desirable in recent years as society has moved towards less complex and more functional products. Getting more uses out of a product is a greener solution for the environment as well [2]. An example of a transformer is shown below. In Figure 1, the transformer is in the state of two chairs.

Figure 1 Transformer in Chair State [4]

In Figure 2, the two chairs have been flipped and pushed together to form a table, the second state. What was originally the seat is now more covered, while the back of the chair becomes more exposed.

Table 1: Transformation Principles and Facilitators [5]

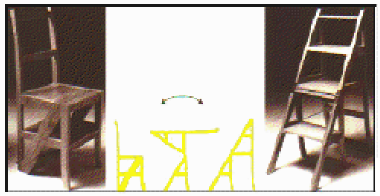
Principles					
Expand/Collapse 		Expose/Cover 		Fuse/Divide 	
Facilitators					
Conform with Structural Interface	Flip	Interchange Working Organ	Roll/Wrap/Coil	Share Power Transmission	Utilize Composites
Enclose	Furcate	Modularize	Share Core Structure	Shell	Utilize Generic Connections
Fan	Inflate	Nest	Share Functions	Telescope	

Figure 2: Transformer in Table State

This product demonstrates the facilitator, flip, which fits under the umbrella principle of Expose/Cover. In Table 1, all three principles are shown along with the 19 facilitators. These principles and facilitators were found doing a heavy search on existing transformers and were used to create the basis of Transformational Design Theory. This study also found that certain principles and facilitators are more popular in different domains and suggests a hierarchy of when they should be used in each one [1].

1.2 CONCEPT GENERATION AND INVESTIGATION METHODS

1.2.1 ALL PRODUCTS

Intuitive concept generation methods exist for a more general product design approach such as the most commonly known, brainstorming. Other methods include 6-3-5 (C-Sketch), Mindmapping, Wordtrees, and Morphological Matricies (6). These methods thrive on the user's creativity and inspiration to have unique ideas for a product. The current system's design is not a focal point,as the goal is think outside of what has been created.

Directive methods such as Force Flow Analysis, Function Structures, and Black Box Diagrams are often used to analyze the current state of a design to see where improvement can be made in their design (6). These methods are commonly used in situations where a design has already been created but is being reverse engineered.

1.2.2 TRANSFORMERS

Transformation design requires a unique blend of intuitive and directive methods. Two or more states of a product already exist and a new, novel combination of these concepts must be concocted. Various methods currently exist that lean more towards intuitive and some exist that are directive.

Wordtree and mindmapping methods can be used with principles and facilitators as key words to help ideation. Using facilitator words while doing these processes has increased the amount of concepts that are generated by 25-30% (5). A more investigative process, The Storyboarding Method, requires users to analyze each state and see how they can mechancially fit together (7). In Figure 3 below, the example is used of a toy that will transform from a soap holder to a humanoid, to a boat.

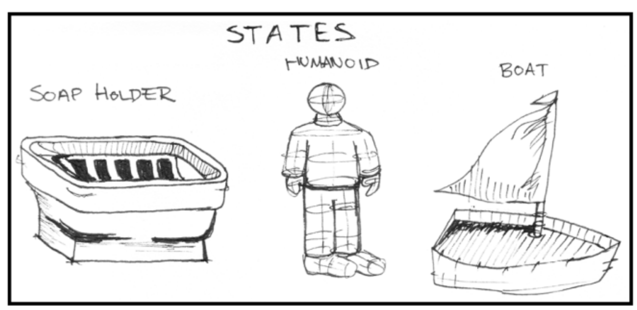


Figure 3: States of Transformer Toy

These states are then analyzed to determine what underlying physical structure exist in terms of where their joints are and where their degrees of freedom, as shown in Figure 4. These skeletons are then matched up to each other ad hoc, to see where the best opportunities lie for transformation, as shown in

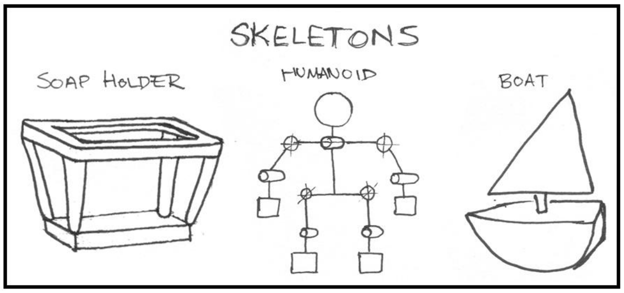


Figure 4: Skeletons of States

Figure 5. These sets of items that transform (parts on the same arrow) are referred to as structure groups.

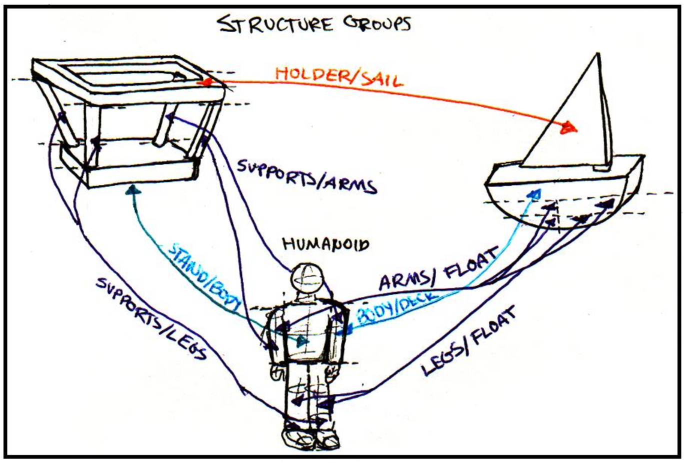


Figure 5: Structure Groups

These ideas are then iterated on until the designer is satisfied with their integration with each other. They continue to draw out their plans of this and skeletal placement as show in Figure 6. From this point, mock-ups and designs can be created.

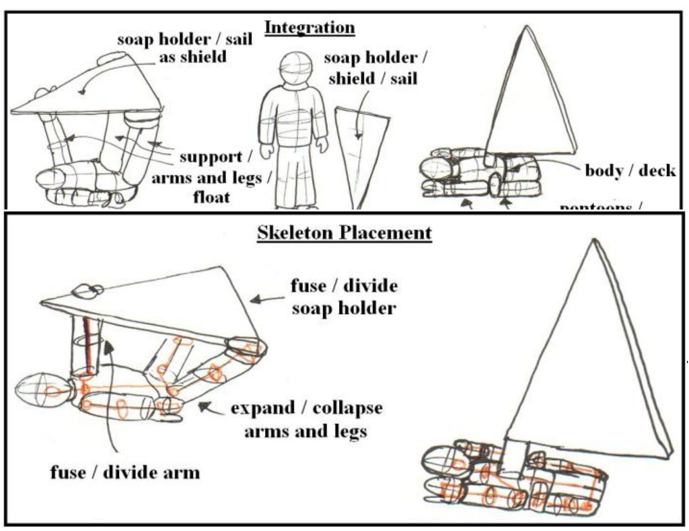


Figure 6: Integration and Skeletal Placement

It has yet to be determined what the best approach to transformation design is in terms of balance of intuition and directive thought processes. The Transformer Diagram Matching Method takes a first attempt to bridge these two needs by having a first step where the designer analyzes each state in terms of several parameters, then a second step where they generate concepts based on the principals and facilitators. Linking the principals and facilitator directively to the design at hand is something that has not been done. This method used a directive method followed by an intuitive method.

This method was also created to expand possibilities for Transformation Design Theory. As this is a very new field, many stepping stones are still underway before the design theories and methodologies are thoroughly understood. This approach also makes use of a more visual intuition to solve design problems. The diagrams are created with emphasis on certain types of features on the design, so that areas with lots of possibilities call out to your eyes much easier and quicker.

3. RESEARCH APPROACH

In order to find the most important components to be included in the diagrams a dual approach was taken, as shown in Figure 7 below. First, several products were brainstormed that would be capable of transformation. Then, they were created into transformers ad hoc, with knowledge of the principles and facilitators. There were specific relationships that started to occur in all the transformations that heuristics were created from. Then using these heuristics, Concept Opportunity Diagrams were designed along with the Constituent Relationship Chart. These were then used to solve new transformation design problems. They are now being compared to the ad hoc designs, and being re strategized to become more useful to the designer.

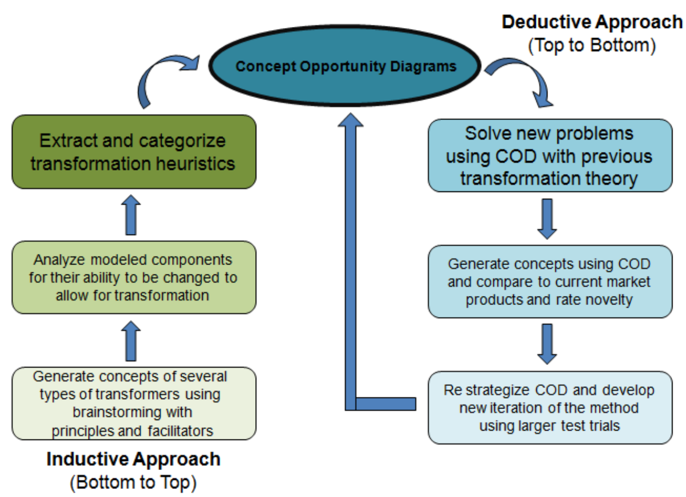


Figure 7: Research Approach

3.1 BRAINSTORMING

Over 50 drawn concepts were brainstormed focusing on principles and facilitators. They ranged in industry including house wares, entertainment, medical devices, transportation, and packaging. Most of the concepts were intended to be table top size and have a limited number of parts so they could be easily prototyped. In Figure 8, you can see a few examples of concepts that were generated. On the top left is a take out container that has snap-in utensils. The top right is a kid's toy xylophone that can be flipped, folded and pushed into a toy guitar, and the bottom design is a backpack that can fully zip open and closed to expose or cover a full workstation.

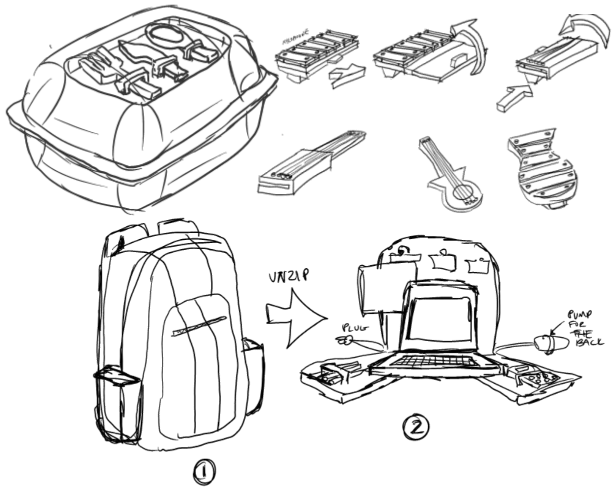


Figure 8: Assorted Sketches of Brainstorming Concepts

3.2 TRANSFORMATION ENABLEMENT HEURISTICS

From this brainstorming process, a number of heuristics were determined to be the focal point of how a state can be transformed. Generally speaking, mechanical designs in each state have several parameters that can range from very constrained to almost anything being possible. This amount of "flexibility" within the design is what determines what types of principles and facilitators are feasible. There are four foundational kinds of flexibility that allow the designer to see opportunities for transformation. These foundational flexibilities are looking at the number of components, degrees of freedom, general shape, and dimensions of each component within the product states.

3.2.1 COMPONENTS WITHIN THE PRODUCT STATES

First, when looking at each state, we must determine what the critical parts are to each one. We also must look and see if any parts could be simplified into a single part. This is the first step in creating a concept opportunity diagram. *Create an exploded view diagram of each product state using a separate "block" for each component. Maintain shape and aspect ratio as close as possible to the physical product state. If there is a group of components within a product with little to no flexibility, it is appropriate to simplify as a single component. There is a tradeoff between simplifying this process for time purposes and obtaining a greater number of novel ideas.* An example of this can be seen in Figure 9, where a stapler has been broken down into components. In this example, the designer has chosen not to show the full subassembly of the stapling mechanism, as they are choosing to focus on other aspects of the design. However, iterations of different blocks could be done to show the different components.

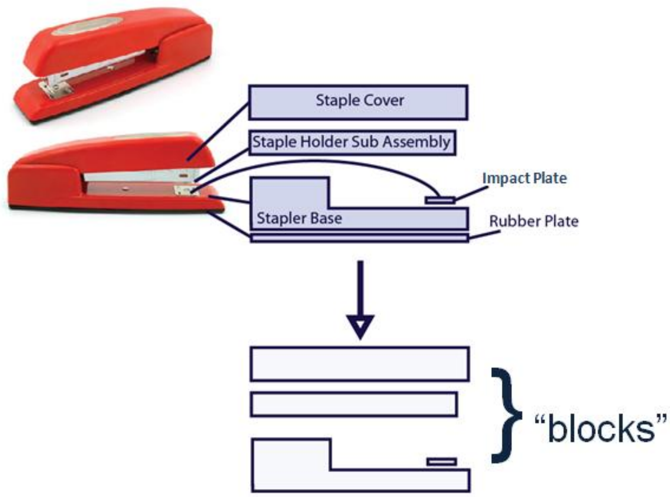


Figure 9: A Stapler Broken Down Into Blocks

3.2.2 DEGREES OF FREEDOM

When looking at the blocks on the Concept Opportunity Diagram, we are curious to see how the components in the product interact with each other. It must be determined if each component can be more or less constrained. For example, a lamp shade may initially be misinterpreted as fully constrained to the lamp holder and light, but it is usually possible to rotate it about the z-axis. Finding these forgotten degrees of freedom with each state allow the designer to find opportunities for specific facilitators that are mentioned in the Constituent Relationship Chart. *Show the degrees of freedom between each part by modeling connections with symbolic lines, as shown in Figure 10. If degrees of freedom can be added, do so. Each line represents a constraint in the x, y, or z direction of translation or rotation.*

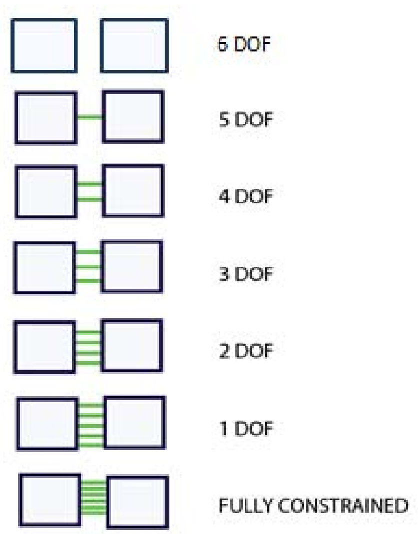


Figure 10: Degrees of Freedom Symbols

This can be applied to the stapler, as shown in Figure 11 below.

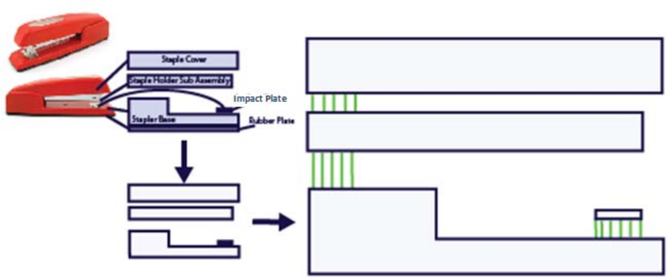


Figure 11: Degrees of Freedom Applied to the Stapler

3.2.3 SHAPE FLEXIBILTY

Next, the designer must look at how fixed the shape of each component is. This is another item that is tends to be seen as more constrained than it really is at first glance. A good example of seeing finding the minimum shape constraint is Frank Gehry's Dancing House in Prague, as shown in Figure 12. He finds the minimal shape constraint and works around it.

Figure 12: Dancing House, Frank Gehry

Looking at the diagram, it must be determined if shape only matters at specific interfaces between components. *Model the portion of the component with fixed or constrained shape by using diagonal lines. If the shape is flexible, leave the portion of the component blank, white, or empty.* An example of this is a key, as shown in Figure 13. The handle part of the key is not truly constrained as to what it looks like; it could practically be any shape. However, the right portion of the key must fit exactly into the door and no geometric changes can be made.

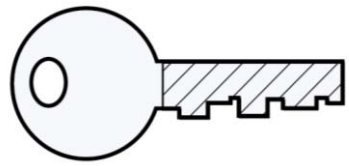


Figure 13: Shape Flexibility of a Key

In Figure 14, Shape Flexibility is shown on the stapler. This step is slightly subjective and in the eyes of the beholder, however it is the exercise of seeing where the shape has freedom that will bring insight.

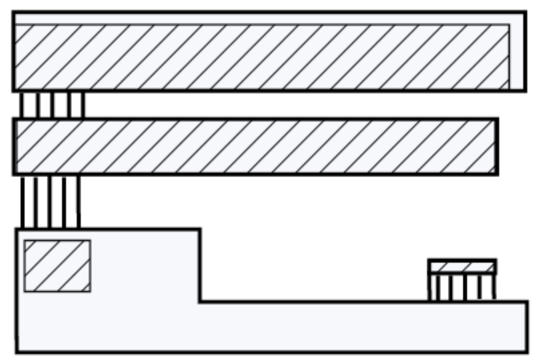


Figure 14: Shape Flexibility applied to the Stapler

3.2.4 DIMENSIONAL FLEXIBILTY

Last, the designer must analyze the dimensions and scales of the components. *Look at the current state border of the component with a solid line but consider the possibilities of decreasing or increasing dimensions. Model these possibilities with dotted lines.* The model for this is shown in Figure 15.

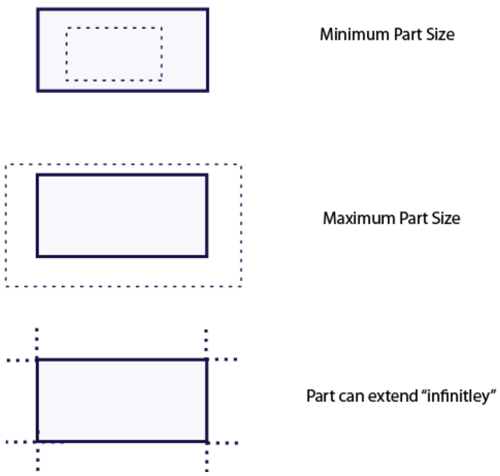


Figure 15: Dimensional Flexibility Model

This step is taken so the designer must consider the possible scale relationships between components as they could see transformations that could be possible in other scale layouts besides the one drawn. Again, this step is a bit subjective, but the more movable they can visualize their constraints, the more successful they will be. This step is shown applied to the stapler in Figure 17.

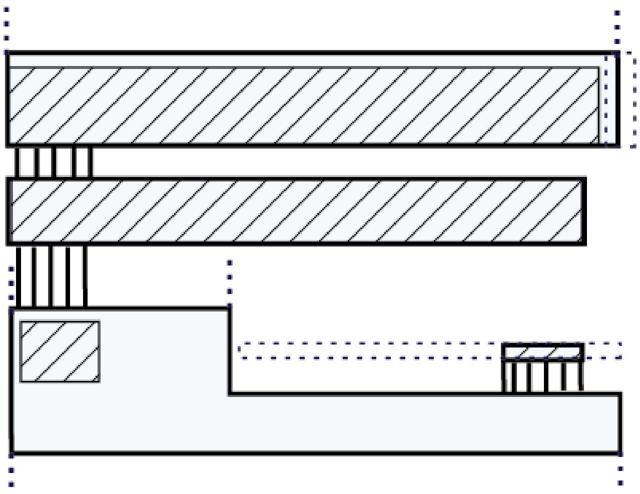


Figure 17: Dimensional Flexibility Applied to Stapler

4 CONSTITUTUENT RELATIONSHIP CHART

After more than one state is diagrammed using the Concept Opportunity Diagram method, the states can be looked at using the Constituent Relationship Chart. As the chart considers the hierarchy of facilitators found in previous research, a different relationship chart exists for the domain of tools, storage, vehicles, structures, and organisms. An example of a concept that could be found from looking at the Constituent Relationship Chart is by looking at Shell. The Constituent Relationship Chart says "Focus on components that are large with freedom on the inside. Also focus on smaller components that only exist in one state." When looking at degrees of freedom it asks "Is there a degree of freedom existing in the large component that would allow the smaller component to be stored inside and then become accessible? If not, can one we added?" In terms of dimensional flexibility it asks "Can the wall thickness and size of the larger component be adjusted to allow the smaller component in? Create as many configurations as possible." In terms of shape it asks "Can the larger component take on the shape of the smaller component or vice versa to allow for more configurations? From these questions, the designer can begin to generate concepts of different ways that the two states could interact. An example of some sketches they might have of two components from two different states interacting is shown in Figure 18. The full constituent relationship chart for each domain can be found in Appendix B.

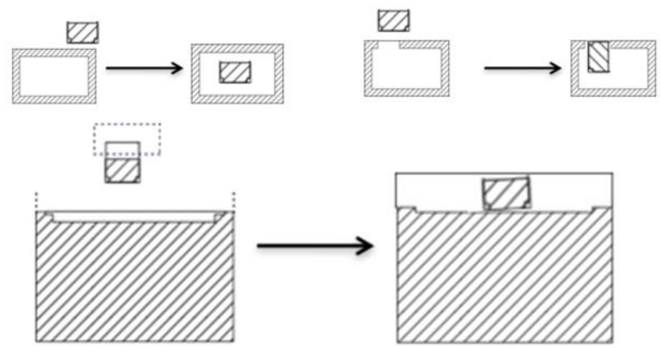


Figure 18: Possible Concepts from using Shell on the Constituent Relationship Chart

5 SOLVING NEW DESIGN PROBLEMS WITH THE METHOD

5.1 CREATING CONCEPT OPPORTUNITY DIAGRAMS

In this example, the stapler will be used along with a hole punch (Figure 19), USB (Figure 20), and light (Figure 21) to look for the possibilities of creating an all in one device. As this method can be somewhat interpretive, there may not be a specific correct way to design a particular device. However, the more thought that is put into the diagram, and the more they are discussed or thought about, the more valuable they become to a design team. When Concept Opportunity Diagrams are created of each object previously mentioned, you end up with the following:

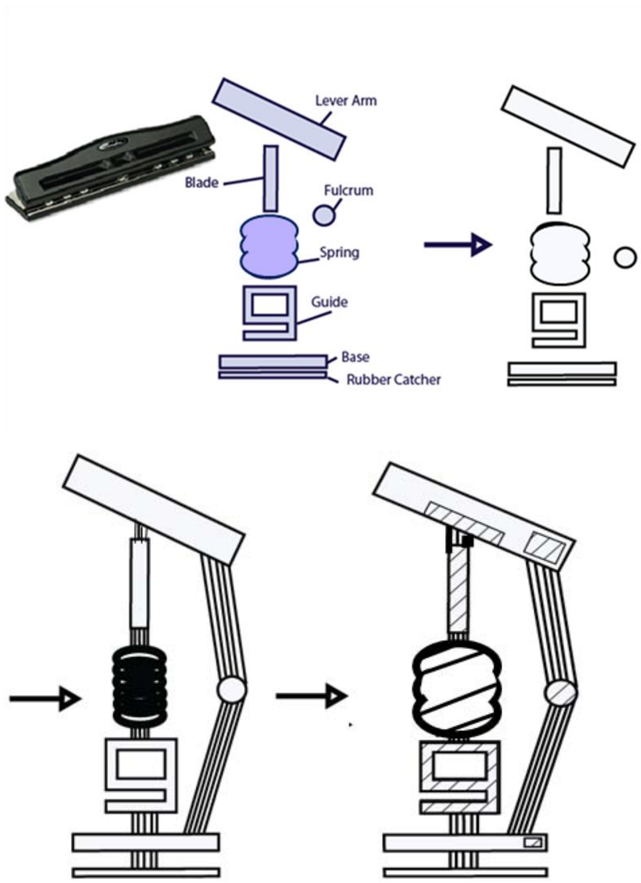


Figure 19: Concept Opportunity Diagram of a Hole Punch

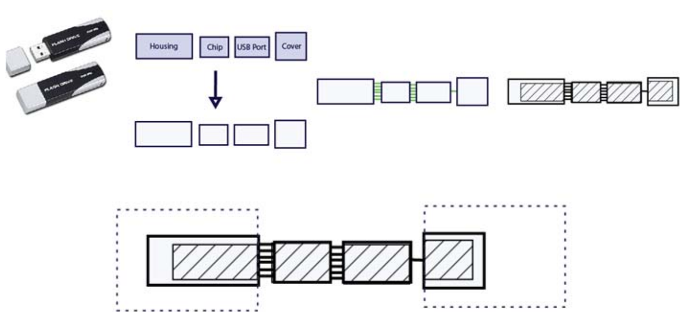


Figure 20: Concept Opportunity Diagram of a USB

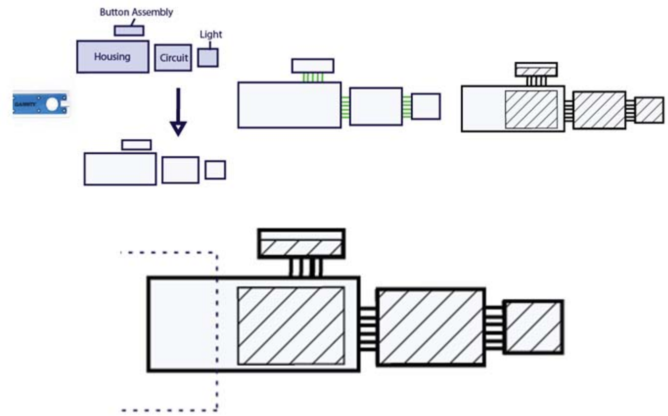


Figure 21: Concept Opportunity Diagram of a Light

5.2 USING THE CONSTITUENT RELATIONSHIP CHART

In Appendix A, the step by step process is given for creating Concept Opportunity Diagrams. After the diagrams are created, the designer used the Constituent Relationship chart to see what concepts could be created. This was done in the order as shown on the chart, which is located in Appendix B. The Constituent Relationship Chart has the designer walk through all the facilitators in order of likely application of their design and allows them to find the potentials of the states for each relationship in terms of the foundations of flexibility previously defined. While using this chart with the diagrams, the designer keeps a running list of their sketches and concepts. Over 70 concepts were created, as some are shown in Figure 22, Figure 23, and Figure 24.

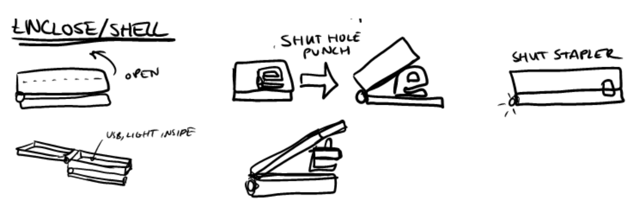


Figure 22: Concepts for Shell for the Device from the Constituent Relationship Chart

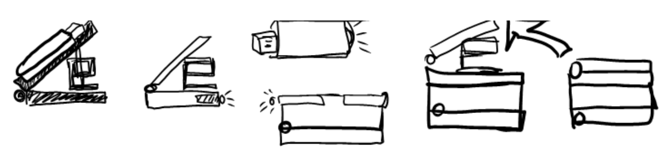


Figure 23: Concepts for Conform to Structural Interface for the Device from the Constituent Relationship Chart

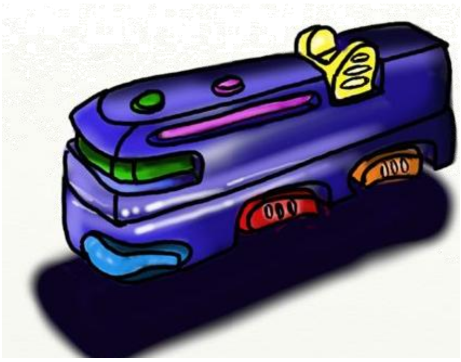


Figure 3: Concept for All-In-One Office Supply

5.3 MOVE FORWARD WITH A SINGULAR DESIGN CONCEPT

After generating several concepts, the top solutions stood out as they offered the most integrated systems. The final design is shown in Figure 25 below. It also had enough extra space in the design for a pencil to be added to the system and ended up being shaped in such a way that allowed it to look like a turtle. On the left, the picture shows how the USB and pen can be removed from the device. It also shows the light and the button pressed to activate it. The middle pictures show how the a leaf spring in the bottom part of the device can be accessed and pressed so that the stapling mechanism pops up and is accessible to the user. The bottom right picture shows how the top piece can be flipped up and around (like a nail clipper) and can be used as a lever for a whole punch. Overall the device can be put in a turtle shaped case, as shown on the top right. The bottom left is the picture of the parts used in the subassembly before it was created. Figure 26 shows a picture of the mechanical model.

Figure 25: Final Product of Office Supply Transformer

6 CONCLUSION

Using the two step process of the Concept Opportunity Diagrams and the Constituent Relationship Chart allows the user to become familiar with the states they are working with and the potential relationships with the transformation principles. This process brings valuable insight to the designer and/or the team and allows them to come up with several ideas for their transforming product that are also much more realistic. This process takes transformation design methodology a large step forward by bridging its two ways of design together, directive and intuitive. This allowed the used to come up with concepts that they would not have otherwise.

7 FUTURE WORK

This method is the first official attempt of this two step process. It is likely that iterations down the road will allow this to be a simplified process that becomes more integrated and streamlined. Also, it is not known whether transformer ideas are best generated when thinking more about the specific product (directive) or the general design principles (intuitive), so the correct balance or order has not yet been determined. A way to test this is to compare quantity and quality of concepts generated in groups against the storyboarding method or 6-3-5 and mind mapping methods.

Different kinds of designs (tools versus organisms) require different Constituent Relationship Charts. As this study focused on the Tool Constituent Relationship Chart, it allowed the chart to be adapting accordingly. Slightly different methods may need to be used for a design, such as storage, where only one state may be known and the goal of the 2nd state is to make it as small as possible.

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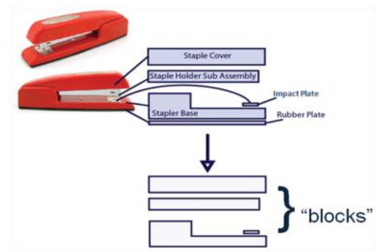
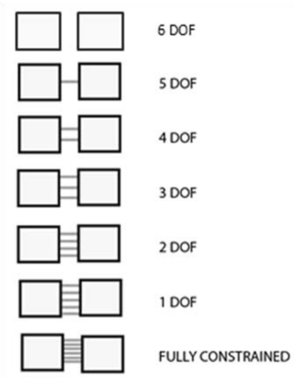
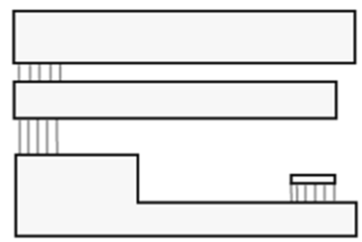
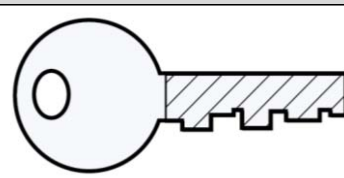
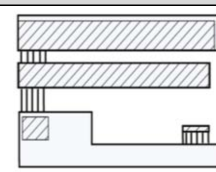
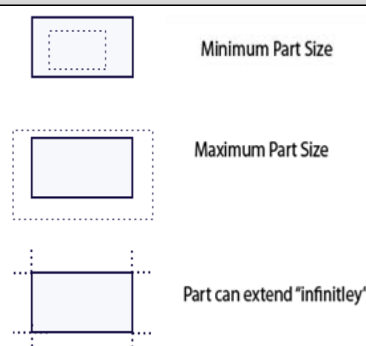
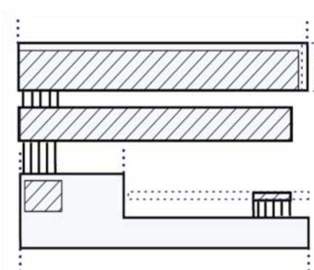
APPENDIX A: STEP BY STEP PROCESS OF CONCEPT OPPORTUNITY DIAGRAM CREATION

Step	Definintion	Guidelines	Example
Definition of States and their Components			
1	Create an exploded view diagram of each product state using a separate "block" for each component. Maintain shape and aspect ratio as close as possible to the physical product state. If there is a group of components within a product with little to no flexibility, it is appropriate to simplify as a single component. There is a tradeoff between simplifying this process for time purposes and obtaining a greater number of novel ideas.		
Degrees of Freedom			
2	Show the degrees of freedom between each part by modeling connections with symbolic lines, as shown in Figure 10. If degrees of freedom can be added, do so. Each line represents a constraint in the x, y, or z direction of translation or rotation.		
Shape Flexibility			
3	Model the portion of the component with fixed or constrained shape by using diagonal lines. If the shape is flexible, leave the portion of the component blank, white, or empty.		
Dimensional Flexibility			
4	Look at the current state border of the component with a solid line but consider the possibilities of decreasing or increasing dimensions. Model these possibilities with dotted lines.		

APPENDIX B: CONSTITUENT RELATIONSHIP CHART FOR TOOLS

Facilitators	Components	Degrees of Freedom	Dimensional Flexibility	Shape Flexibility
1) Conform w/ Structural Interfaces	Is there the same number of components in both states? Can components of one fit on the surface of the other?	Can a degree of freedom be added to an existing joint such that the integrity of the design will not be harmed? If not, is there a place a component can be broken down into smaller components in the other state?	Is there a side of a component on one state that could fit onto the surface of a component of another state?	Could the shape of one of the components adjust to accommodate the other so the so they can share a surface?
2) Share Functions	Focus on components that are in both states that have the same functionality. Can they be streamlined into a single part?	Do both have the same degrees of freedom? If not, can degrees of freedom be added in the more constrained state?	Does size allow them to be consolidated into one shape?	Does geometry allow them to be consolidated into one shape?
3) Segment	Do parts exist with large aspect ratios that could be broken down?	Is there a component that contains an axis of symmetry? Can a degree of freedom (likely rotation) be added to this axis?	Can the aspect ratio be changed so it can be controlled easier?	Can the shape be made more uniform so it can be segmented more easily?
4) Shell	Focus on components that are large with shape freedom on the inside. Also focus on smaller components that only exist in one state.	Is there a degree of freedom existing in the large component that would allow the smaller component to be stored inside and then become accessible? If not, can one we added?	Can the wall thickness and size of the larger component be adjusted to allow the smaller component in?	Can the larger component take on the shape of the smaller component or vice versa to allow for more configurations?
5) Nest	Focus on components that are similar in size or have a limb on them that is similar in size to another component.	Do these components have a degree of freedom that allows them to be stacked? Can one be added?	Can a draft be added to allow parts to stack?	Can the shape of the components be adjusted to allow for a better male/female fit while nesting?
6) Modularize	Focus on components that are only used in one state and are only connected to one or two other components.	Can this component be removed from the system and easily put back without compromising its capabilities?	Is there a place the modular component can be stored within the rest of the system?	Can multiple components from different states be attached at the same point to allow for different attachments? Can uniform attachment shapes be used?
7) Flip	Focus on components that are only used in one state. See where they attach to the rest of the device and see if a point of symmetry (an axis to rotate about) can	Is there a degree of freedom existing that would allow the item to flip correctly? Could one be added at the point of symmetry?	Can the size of the flipping components be adjust better to allow for the components not currently being used to be hidden or removed?	Can the size of the flipping components be adjusted better to allow for the components not currently being used to be hidden or removed?

	be found in between them.			
8) Fold	Focus on components that are only used in one state. See where they attach to the rest of the device and see if a line of symmetry can be found in between them.	Is there a degree of freedom existing that would allow the item to fold correctly? Could one be added at the line of symmetry?	Can the size of the flipping components be adjust better to allow for the components not currently being used to be hidden or removed?	Can the size of the flipping components be adjust better to allow for the components not currently being used to be hidden or removed?
9) Share Core Structure	Focus on components that are in both states or are very similar	Do both have the same degrees of freedom? If not, can access of degrees of freedom be removed in the more constrained state?	Can one dimension be used for both states? If not, how much can be shared?	Can the similar parts be consolidated into one shape?
10)Enclose	Focus on components that are large with freedom on the inside. Also focus on smaller components that only exist in one state.	Is there a degree of freedom existing in the large component that would allow the smaller component to be stored inside and then become accessible? If not, can one we added?	Can the wall thickness and size of the larger component be adjusted to allow the smaller component on? Create as many configurations as possible	Can the larger component take on the shape of the smaller component or vice versa to allow for more configurations?
11) Share Power Transmission	Focus on components that require power. Can they be streamlined into a single system?	Can the power drive all the components without affecting the degree of freedom too much?	Can the power drive all the components without requiring too much reconstruction of the system?	Can the power drive all the components without requiring the shape to be hindered?
12) Utilize Composite	Use composites if one state is/or almost is a subsystem of the other state	Can the non-subsystem part be easily removed?	Can size be optimized for both states?	Can shape be optimized for both states?
13) Utilize Generic Connections	Focus on components that are only used in one state and are only connected to one or two other components.	Can this component be removed from the system and easily put back without compromising its capabilities?	Is there a place the modular component can be stored within the rest of the system?	Can multiple components from different states be attached at the same point to allow for different attachments? Can uniform attachment shapes be used?
14) Fan	Focus on components that are only used in one state. See where they attach to the rest of the device and see if a point of symmetry (an axis to rotate about) can be found in between them.	Is there a degree of freedom existing that would allow the item to fan correctly? Could one be added at the point of symmetry?	Can the size of the fanning components be adjusted better to allow for the components not currently being used to be hidden or removed?	Can the shape of the fanning components be adjusted better to allow for the components not currently being used to be hidden or removed?

15) Telescope	Focus on components that are only used in one state with a large aspect ratio.	Does this component require minimal attachment to the rest of the state?	Could the flexible component fit appropriately into the other state when put into its storage position?	Could the shape of the other state be adjusted to accept the storage of the flexible material?
16) Roll/ Wrap/ Coil (flex material)	Focus on components that exist in one state that can make use of flexible materials or that have large aspect ratios.	Does this component require minimal attachment to the rest of the state?	Could the changing component fit appropriately into the other state when put into its storage position?	Could the shape of the other state be adjusted to accept the storage of the changing component?
17) Furcate (flex material)	Focus on components that exist in one state that can make use of flexible materials or that have large aspect ratios that allow the part to be broken into thin attached sections.	Does this component require minimal attachment to the rest of the state?	Could the changing component fit appropriately into the other state when put into its storage position?	Could the shape of the other state be adjusted to accept the storage of the changing component?
18) Interchange Working Organ	This is used in transformers where states have the same/similar core structure but a different power source is used.	Do the degrees of freedom allow for the power source to easily be interchanged?	Is the design the right size to allow for multiple power sources within the structure?	Does the shape allow for multiple power sources within the structure?
19) Inflate	This is used where one state has a core structure that is much larger than the other state.	Are the degrees of freedom compromised in either state from inflation or deflation?	Can the size of either state change to accommodate the needs of shape for inflation?	Can the shape of either state change to accommodate the needs of shape for inflation?