The Pennsylvania State University

The Graduate School

Department of Mechanical and Nuclear Engineering

STUDY OF RECONFIGURABILITY AND RECONFIGURABLE PRODUCTS FOR USE IN DESIGN

A Thesis in

Mechanical Engineering

by

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Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

May 2010

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ABSTRACT

Reconfigurable systems are able to meet the increasingly diverse needs of consumers. A reconfigurable system is able to change its configuration repeatedly and reversibly to match the customer's needs or the surrounding environment, allowing the system to meet multiple requirements. In this paper, a large sample of reconfigurable products was collected and studied in order to obtain a better understanding of reconfigurable products as a whole. The sample of products was broken down with respect to area of reconfigurability, reconfiguration process utilized, incorporation of adjustability and sizing, number of configurations, and size of the product., while trying to identify any distinguishing characteristics or trends. The main properties identified were the areas in which reconfigurability has been applied to products, the relationship between how a product reconfigures and the number of configurations in the product, and the four means by which products with multiple configurations reconfigure. This is an extension of previous work wherein only three methods of reconfiguration were identified. Several example products demonstrate that the previously identified methods were not inclusive and the necessity of the fourth reconfiguration mode. The value of this approach is demonstrated through two example products to show how they can be utilized in the development of new reconfigurable products.

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ACKNOWLEDGEMENTS

This research was partially funded by the National Science Foundation under grants no. 0729386 and no. 0846373.

CHAPTER I

INTRODUCTION

The objective of this thesis is to identify distinguishing characteristics and trends within reconfigurable products that will aid designers in the concept identification and generation phases of new reconfigurable product development. There will be particular emphasis placed on the area of Designing for Human Variability (DfHV). The principle contributions of this work are the identification of areas in which reconfigurability is applied, the expansion of the current list of methods by which products with multiple configurations reconfigure, and the suggestion that designers focused on the creation of a reconfigurable product with two configurations first considers the use of transposition.

There is a growing desire for products that can meet multiple consumer needs. Reconfigurable systems are one method of accomplishing this goal, since they are able to change their configuration to match the varying environments or customer needs [71]. This ability creates interesting opportunities since the system reconfigures to different states at different times to match the exact task at hand, instead of being in one static state that has been designed for the worst-case scenario [75]. One key element to reconfigurable systems is that these systems are able to change their configuration both *repeatedly and reversibly* [61]. Figure 1.1 shows a simple example of a reconfigurable system. The product is able to be a chair or a step stool depending on the user's needs and is able to obtain both of these configurations as often as required.

Reconfigurable products have been around for centuries; the folding hand fan was invented in Japan in the 7th century [57]. However, the majority of reconfigurable products and concepts are from more recent times. Unfortunately, little work has been done to better understand these products and how to design them. Important factors such

Figure 1.1: An example of a reconfigurable system, where a step ladder is being reconfigured into a chair. This process can be repeated and reversed [1].

as when to design a reconfigurable product and how to incorporate reconfigurability have been overlooked in the majority of reconfigurability research.

Reconfigurable systems can exhibit either a unique configuration every time or be limited to a fixed set of distinct configurations [61]. In theory, each configuration is replacing a dedicated product; one designed with a single specific function in mind. An example of a reconfigurable system with unique configurations is the *FlexibleLove*, pictured in Figure 1.2(a). This chair, made of an "accordion-like, honeycomb" structure, can be configured countless ways. An example of a reconfigurable system with limited distinct configurations is DB Flecher's Capstan table, pictured in Figure 1.2(b). It can change from a large table to a smaller one and vice versa.

(a) Unique (b) Fixed

Figure 1.2: Products representing the two classifications for the number of configuration obtainable with a product: unique or limited [2, 3].

The manufacturing of reconfigurable products creates several benefits for both the consumer and the manufacturer. These benefits include: reduction in space, weight, and price, the possible creation of functions between states, and economies of scale. The reduction in space, weight, and price comes from all dedicated products being replaced compared to the one reconfigurable product replacing them. For example, in Figure 1.1, the combination chair/step stool would take up less space than both a chair and a step stool combined. It could also weigh less, since it is one product compared to two. The chair/step stool may weigh more than a dedicated chair or step stool by itself, because of the added material used to make the product reconfigurable. The same is true for the reduction in price. A single reconfigurable product will usually cost more than a single dedicated product being replaced. However, when the price of all dedicated products being replaced is compared to the price of the single reconfigurable product, there can be a significant reduction. A reconfigurable product may also provide functions between states that would not be available with dedicated products. For example, the *FlexibleLove* (Figure 1.2(a)) is able to bend and twist to create shapes that are not seen with typical furniture. Finally, economies of scale are *an increase in efficiency of production as the number of goods being produced increases* [52]. Reconfigurable products allow a company to achieve economies of scale since the company will be producing one reconfigurable product instead of several dedicated products. The larger production quantity of the reconfigurable product will bring the price down.

In the next chapter, fields related to reconfigurability are presented, as well as past and present research that has been performed in the area of reconfigurability. Chapter III presents a sample of reconfigurable products that are examined and broken down with respect to several product characteristics to better understand reconfigurable products as a whole. Several of the findings from Chapter III are used to generate conceptual reconfigurable products in Chapter IV. Finally, Chapter V discusses the broader contributions of the work, as well as the identification of areas for possible future work.

CHAPTER II

BACKGROUND AND LITERATURE REVIEW

Reconfigurability is a relatively new area of interest in the research community. Work being performed in the area of reconfigurability and parallel fields will be presented in this chapter. This work includes the three main needs addressed by reconfigurable products, work being performed in the field of transformation, several products that are currently being studied in the field of reconfigurability, and methods that have been developed for the incorporation of reconfigurability into products.

2.1 Needs for Reconfigurability

Siddiqi and deWeck identified three main needs addressed by reconfigurability: *multi-ability*, the ability of a system to perform multiple functions or obtain varying operating points over time, but not concurrently, *evolution*, the ability to morph the system into future planned or unplanned configurations, and *survivability*, the ability of a system to partially operate despite a failure in some components or subsystems [75]. Figure 2.1 shows a decomposition of these requirements. A reconfigurable product can exhibit anywhere from one to all three of these needs.

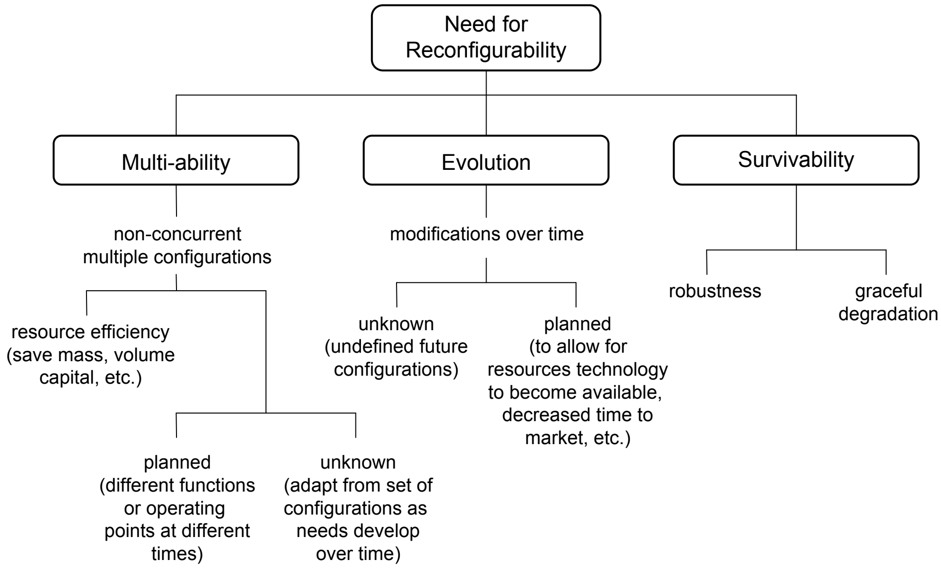


Figure 2.1: A decomposition of the three main needs addressed by reconfigurability [75].

2.2 Related Fields

Reconfigurability has many related fields, including: flexibility, changeable systems, and transformation. Each field pertains to products with multiple configurations, but slight variations distinguish one field from another.

The definitions of flexibility and reconfigurability provided by Ferguson et al. 2007 will be used in this paper. Flexibility is defined as *the property of a system that promotes change in both the design and performance space*, while reconfigurability is given as *a subset of flexibility in which system configurations can be changed repeatedly and reversibly.* Nevertheless, reconfigurability and flexibility are sometimes used interchangeably. There are two papers, Ferguson and Lewis [63] and Olewnik et al. [71], where reconfigurable systems and flexible systems are given the same definition: *systems designed to maintain a high level of performance through real-time change in their configuration when operating conditions or requirements change in a predictable or unpredictable way.*

Flexible and reconfigurable systems are also subsets of changeable systems. A changeable system is defined as *systems whose configurations can be changed, altered, or modified, with or without external influence after the system has been deployed* [61].

A transformer is *a system that changes state in order to facilitate new or enhance existing functionality* [76]. Based on the definitions of a transformer and a reconfigurable system, a reconfigurable system is also a subset of a transformer.

The distinction between the varying fields can be vague. All fields appear similar, with each using slightly different definitions to describe products that are able to achieve multiple configurations. Flexible systems focus on the change in the design and performance space, changeable systems focus on the change after the system has been deployed, and transformers focus on new or enhanced functionality. The field that is of particular interest for this paper, however, is transformation. The work being performed in the field of transformation is similar to some of the work performed for this research. A detailed look at the work being performed in the field of transformation is provided in the next section.

2.2.1 Transformation

Much of the work on transformers has been in the identification and use of *transformation principles* and *facilitators*. Singh et al. [76] studied a large sample of transforming products to identify the methods in which these products transform. The intention is to assist the designer when incorporating transformation into their designs. Both an inductive and a deductive approach were used to identify transformation principles; *generalized directives to bring about certain mechanical transformations.* In other words, a transformation principle is a generalized description of the method utilized by a product to transfer between configurations. The three transformation principles identified are:

- **Expand/collapse:** changing the physical dimension of an object to bring about an increase/decrease in occupied volume primarily along an axis, in a plane, or in three dimensions.
- **Expose/cover:** revealing or concealing a new surface to alter functionality.
- **Fuse/divide:** making a single functional device become two or more devices, at least one of which has its own distinct functionality defined by the state of the transformer.

Transformation facilitators were also defined using the same method. They are *design constructs that aid in creating mechanical transformation, but their implementation does not create transformation singly.* Therefore, the transformation facilitators compliment the transformation principles. Singh et al. listed 20 transformation facilitators, detailed in [76]. A follow up on the use of transformation principles and facilitators and how they relate to one another when used in reconfigurable products was conducted by Weaver et al. [79].

Methods have also been identified for the implementation of the transformation principles and facilitators in the concept generation phase of the new product design process for a transforming product [78, 77]. Skiles et al. [78] presents a method for the use of transformation principles in mind mapping. Singh et al. [77] presents a complete methodology for Design for Transformation with the use of transformation principles and facilitators in concept generation using transformation cards ("T-cards"), design by analogy, and mind mapping. Mind mapping with transformation principles has been utilized in a few other papers as well [62, 76].

2.3 Reconfigurable Research Products

Several products have been extensively studied in the research community in recent years. Four main areas of interest have been reconfigurable manufacturing systems and tools, morphing aircrafts, self-reconfigurable modular robots, and planetary surface vehicles. Each product will be described in detail below.

2.3.1 Reconfigurable Manufacturing Systems and Tools

Since the end of the 1990s, many manufacturing companies have been looking forward to the possible implementation of a reconfigurable manufacturing system (RMS). It is believed that RMSs, with the advantages of both dedicated manufacturing systems and flexible manufacturing systems, will provide the best economic solution for manufacturers [68]. These systems are capable of being quickly adapted to changing market requirements by providing the needed functionality and capacity at any time [73]. Reconfigurable manufacturing systems have the main goal of using modules that can be rearranged rapidly for the quick integration of new technologies into existing systems [59]. In order for an RMS to be reconfigurable it must retain the following key features [73]:

- Modularity: common units to create product variants
- Integrability: interfaces must be open to new integration
- Customizability: machines built around a product family
- Convertibility: short conversion time between production groupings
- Diagnosability: easy to identify problems

In reconfigurable manufacturing systems, the basic building block is the reconfigurable machine tool (RMT). In today's manufacturing industry the majority of the machines are dedicated machine tools (DMT), which are custom-designed tools with one specific function that cannot be converted when a part is changed. Instead, when parts are changed, a whole new machine must be designed and built. In order to avoid this problem, computer numerical controlled (CNC) machines that incorporate vast amounts of flexibility were developed. The problem with the CNC machines are that they are designed prior to the actual product itself and, therefore, tend to have unused resources. On the other hand, the RMT will be designed around a specific part family or set of parts, while being reconfigurable to adapt to any changes in the parts [68]. According to Landers et al., a RMT must be both modular in its construction and convertible. Modular in its construction means that the machine can be reconfigured by simply swapping out entire modules and convertible means that the modules can be repositioned or reoriented without changing the topological characteristics of the machine. There is still work that needs to be done to bring this concept to life.

2.3.2 Morphing Aircraft

NASA has contributed to the field of reconfigurability with their Morphing Project. NASA defines morphing as *efficient, multi-point adaptability including macro, micro, structural and/or fluidic approaches.* The project examines the challenges incorporated with reconfigurability in flight, including vehicle control, adaptability, efficiency, and safety [69]. Their long-term

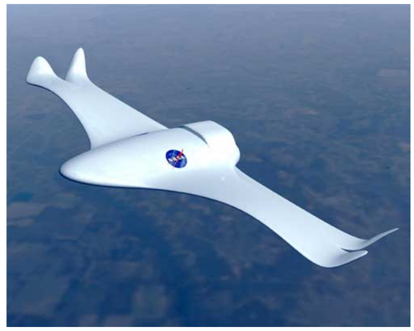


Figure 2.2: A conceptual drawing of NASA's morphing aircraft that will incorporate reconfigurability to handle an array of missions [4].

goal is an aerospace vehicle that can efficiently adapt to handle a wide range of missions, such as the aircraft pictured in Figure 2.2. Some of the benefits of having a vehicle with these capabilities include: versatility to accommodate contradictory mission requirements, resiliency to overcome unforeseen problems, adaptability to improve overall performance, and completion of missions which had previously been thought to be impossible [69].

A major advancement from the Morphing Project has been the DARPA/AFRL/NASA Smart Wing. It is a morphable wing constructed using smart structures, which are structures that can sense what is going on around them and respond through a control system. The wing incorporates a contoured, hingeless flap and aileron designs actuated using built-in SMA tendons that are driven by piezoelectric sensors [67, 80]. Nevertheless, there is still much work required to achieve a completely reconfigurable aerospace vehicle.

2.3.3 Self-Reconfigurable Modular Robots

One reconfigurable system that has gained attention over the years is the self-reconfigurable modular robotic system. The system consists of several small robots that connect together in various ways to obtain different configurations [58]. Self-reconfigurable means that the system can transform into various shapes by changing the connections between the modules without external help. One major benefit of the self-reconfigurable system is self-repair; the system itself can switch out a damaged module with a spare [70].

There are two classes of self-reconfigurable modular robots: lattice and string-type. In

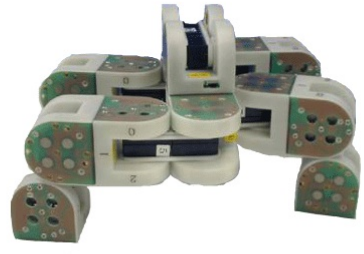


Figure 2.3: Example configuration of a self-reconfigurable robot depicting the dexterity of the modules [5].

the lattice system, all modules are homogeneous and are placed at regular grid points in order for each module to know where the others are located. This type of system has easy self-reconfiguration, but hardware realization is generally complicated. In string-type systems, the modules are heterogeneous and self-reconfiguration tends to be difficult. However, once the modules are joined together, the system is extremely dexterous [70].

The M-TRAN system is one of the more advanced self-reconfigurable modular robotic systems. M-TRAN consists of ten modules that are homogeneous and composed of two semi-cylindrical boxes with a link connecting them. Each box can independently rotate from -90 degrees to 90 degrees around the axes at both ends of the link and has three connection surfaces [70]. This can be better understood from Figure 2.3. The M-TRAN system behaves as a lattice type system for self-reconfiguration and then as a string-type after connection, providing the benefit of both classes.

2.3.4 Planetary Surface Vehicle

A new idea in reconfigurability is the reconfigurable planetary surface vehicle (PSV). This vehicle would be able to take the place of three typical exploration vehicles: the site preparation vehicle (SPV), the long haul vehicle (LHV), and the astronaut transport vehicle (ATV). Comparisons of the vehicles can be found in Table 2.1. In the reconfigurable case, for values that change less that 10 percent between configurations A, B, and C, the components are assumed to remain constant. However, if the components required changing, reconfiguration is achieved through the use of modules.

The paper by Siddiqi and de Weck [75] compares the use of PSVs to the use of SPVs, LHVs, and ATVs on a simulated five-man Mars exploration mission. It was determined that for this mission 1 SPV, 2 LHVs, and 3ATVs were required or 5 PSVs, since the PSV can only perform one task at a time. They found that the mass of the 5 PSVs would be roughly 220 kg less than the combined weight of the SPV, LTVs, and ATVs. In addition, they found that the PSV offers 27 percent more efficiency, in terms of delivering unit transport capabilities per unit mass. They also performed a Markov reliability analysis on the different fleets and discovered that the PSVs were 2.72 times more survivable. Given these results, further research in this area is warranted.

2.4 Reconfigurability Methods

Despite the fact that there are many reconfigurable products readily available on the market, researchers have only recently developed methods to determine when it is most advantageous to introduce reconfigurable products. Also, if it is determined that a reconfigurable product is the best option, methods have been developed to determine how to design the product, i.e., which aspects should be made reconfigurable and to what extent. This section discusses various possible solutions that have been developed for these issues.

Table 2.1: Comparison of the site preparation vehicle (SPV), long haul vehicle (LHV), and astronaut transport vehicle (ATV) with the optimization results for the three configurations, A, B, and C, of the PSV [75].

	SPV	LHV	ATV
Range (km)	5	50	100
Speed (km/hr)	3	8	12
Tow Capacity (kg)	5000	2500	5
Cargo Capacity (kg)	500	200	50
Total power (kW)	2.68	3.46	0.94
Fuel capacity (kg)	2.7	11.4	4.1
Wheelbase (m)	2.54	2.54	2.54
Track (m)	1.52	1.52	1.52
Wheel diameter (m)	1.13	1.12	1.09
Wheel width (m)	0.34	0.28	0.27
Max torque (Nm)	34.6	16.65	2.7
Traction drive power (W)	646	842	211
Total mass (kg)[2]	358	401	245

	A	B	C
Range (km)	8	60	95.7
Speed (km/hr)	0.67	4.5	12.5
Tow Capacity (kg)	5527	2522	42.2
Cargo Capacity (kg)	501	118	171
Total power (kW)	0.73	1.92	1.36
Fuel capacity (kg)	4.48	13.1	5.4
Wheelbase (m)	2.54	2.48	2.48
Track (m)	1.52	1.52	1.48
Wheel diameter (m)	1.13	1.11	1.11
Wheel width (m)	0.32	0.27	0.28
Max torque (Nm)	37.5	15.7	3.9
Traction drive power (W)	156.8	455.6	315.3
Total mass (kg)[2]	245	311	270

2.4.1 Basic Equations

Siddiqi [74] has created a few basic equations to help determine whether or not it is advantageous to develop a reconfigurable system. The first equation is for *relative functional efficiency*. The equation compares the functional efficiency of a reconfigurable system to the group of dedicated systems being replaced and is defined in equations 2.1, 2.2, and 2.3.

$$\Xi_f = \frac{\textit{Functional Efficiency of Reconfigurable System}}{\textit{Functional Efficiency of Dedicated System}} = \frac{\eta_{fR}}{\eta_{fD}} \tag{2.1}$$

$$\eta_{fR} = \frac{\sum_{i=1}^{m} v_i}{\rho} \tag{2.2}$$

where m is the number of number of configurations, v_i is the capability of configuration i, and ρ is the resources (such as cost, mass, etc.) of the reconfigurable system.

$$\eta_{fD} = \frac{\sum_{j=1}^{k} v_j}{\sum_{j=1}^{k} \rho_j} \tag{2.3}$$

where k is the number of dedicated systems being replaced, v_j is the capability of dedicated system j, and ρ_j is the resources of the j^{th} dedicated system.

The second equation created by Siddiqi is for *relative performance efficiency*.

$$\Xi_p = \frac{\textit{Performance Efficiency of Reconfigurable System}}{\textit{Performance Efficiency of Dedicated System}} = \frac{\eta_{pR}}{\eta_{pD}} \tag{2.4}$$

This equation compares the performance efficiency of the reconfigurable systems to a set of dedicated systems, similarly to relative functional efficiency.

For a reconfigurable system to be more advantageous than a set of dedicated systems, both the relative functional efficiency and relative performance efficiency must be greater than 1.

There are two problems with these equations. First, they do not consider the importance of the capabilities of the dedicated systems. For example, a baseball glove used by a professional and a baseball glove used by a Little Leaguer have the same capability (catching the ball). However, in Little League, a player can easily use their one glove to play any position on the field, while in the Major Leagues, it is vital that the glove be tailored to a specific position to provide optimal results. Therefore, the capability of the professional's glove is more important than the capability of the Littler Leaguer's glove. Second, an issue arises when cost is used as the resource in the equations. A specific product's price can vary greatly depending on quality. It can be difficult to determine which dedicated product is of the same quality as the reconfigurable product.

2.4.2 Framework for Flexible System Design

Olewnik and Lewis [72] have created a decision support framework for flexible system design that should make it possible to determine if a certain flexible system will be profitable for a company to produce. Since flexibility and reconfigurability are closely related, their methods may also work for reconfigurable systems.

The framework for flexible systems was generated using the original decision based design framework created by Hazelrigg [64]. There are a few key differences between the two frameworks, however. The main difference is that Hazelrigg provides a loop that maximizes utility with respect to demand and product price. This loop also has the cost of manufacturing and other life cycle costs as inputs. In Olewnik and Lewis [72], there is no such loop. The framework has product price inputted into demand, which is inputted into identifying the budget. The project utility is an information input into these three steps. The majority of the rest of the two frameworks are the same. A diagram of the new flexible system framework is pictured in Figure 2.4. There are nine separate stages. The first eight correspond to an optimization problem that is to identify the best design, while the last stage is for concept generation. The formal problem statement is given as:

max u (corporate utility) [stage 6]

subject to

budget (budget constraint) [stage 6]

a (attribute constraint) [stage 5]

$P(t)$ (price constraint) [stage 5]

The example present in [72] showed no use of mathematics. The example is the design of three rooms with two movable room dividers between them. The moveable range of

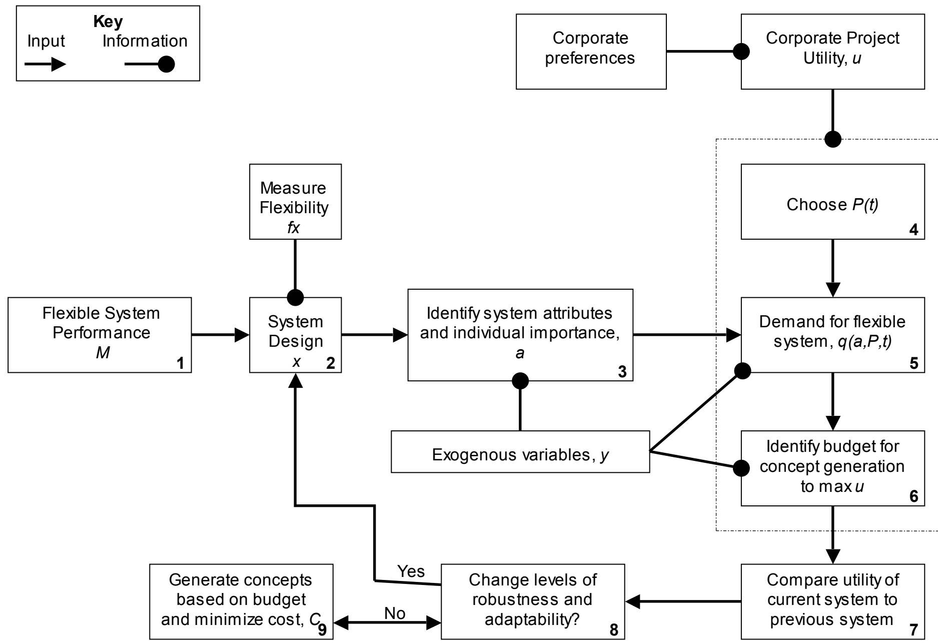


Figure 2.4: Diagram of the decision based design framework for flexible systems. Numbers represented the nine steps of the process [72].

the dividers were set to be 6.1 meters using the framework. It seems that in order to get the best results, however, the range of the dividers should be solved using an optimization problem, allowing for the possibility of differing ranges between the two room dividers.

2.4.3 Multi-Ability in Reconfigurable Systems

In addition to some basic equations, Siddiqi [74] has developed a method for incorporating multi-ability into reconfigurable systems design. Multi-ability is the ability of a system to perform multiple functions over time but not concurrently [61]. This method can be easily applied provided that the different functions or modified functions desired for the system are known in advance and the number of configurations and design variables are relatively small.

Siddiqi uses a design vector $\mathbf{x}_i$, where each i pertains to a different configuration. Then, within each of these configurations there is a set of n design variables.

$$\mathbf{x}_\mathbf{i}^\mathbf{T} = [x_{1i}, ..., x_{ji}, ..., x_{ni}] \tag{2.5}$$

Knowing that there are a total of m possible configurations, a larger vector **X** is defined that incorporates all $\mathbf{x}_i^T$.

$$\mathbf{X^T} = [\mathbf{x_1^T}, ..., \mathbf{x}_i^\mathbf{T}, ..., \mathbf{x}_m^\mathbf{T}] \tag{2.6}$$

Once the above information is decided upon, an optimization problem can be generated in which the objective is to find **X** while maximizing a design criteria, **J**, subject to constraints **g(X)**.

$$min\mathbf{J} = \sum_{j=1}^{p}\sum_{k=1}^{p} m_{jk}z_{jk} \tag{2.7}$$

$$s.t. \quad g_i(X_i) <= 0 \tag{2.8}$$

In the above equation, m_{jk} is the total number of configurations between state j and k and z_{jk} is the cost of reconfiguration between j and k. In Siddiqi's work, the cost of reconfiguration was found using the assumption that the cost is directly related to the amount of mass exchanged from one configuration to another; the greater the mass the greater the reconfiguration cost.

The optimization for each configuration was is carried out using Simulated Annealing. To determine which components were to be static, substituted, or transformed, each component was looked at individually. For components where the change between each configuration was less than 10 percent, they were assumed not to change. For some components, a coefficient of variance was set. If the component stayed below this coefficient of variance, transformation could be used. On the other hand, if the component went above this coefficient, substitution would be used. This method was used for the design of the planetary surface vehicle presented in section 2.3.4.

2.4.4 Family of Reconfigurable Systems

Attempting to provide a variety of products that will meet everyone's needs can be very costly for a company; a company must focus on several different products at one time, each with their own distinct components and manufacturing processes. In order to keep costs low while still providing product variety, many companies utilize product families. Ferguson et al. [60] have developed a possible method for developing a family of products that incorporate different levels of reconfigurability.

Ferguson et al. developed a family of reconfigurable race cars, where the number one driver on the team has the fastest car. The family was developed assuming that the team does not have enough money to make all three team cars fully reconfigurable. Therefore, vertical leveraging was used to create three reconfigurable race cars that fit within their budget. While designing the race cars, they not only had to focus on which aspects to make reconfigurable, but also had to make sure there was an significant amount of commonality among the cars in order to create an effective product family.

There are several steps in this process. The first of which is creating optimized static and fully reconfigurable race cars to compare the teams cars against. Then, Ferguson et al. use a market segmentation grid to determine the core architecture that will create the product family. The next step is the main part of the process, the multilevel multidisciplinary design optimization. The top level of the optimizer, the system-level optimizer, has the job of using a generic algorithm to minimize the performance objective of the entire family, $f(x)$. Then, the three subsystem optimizers, with each pertaining to one of the three race cars, carry out unique performance-based objective functions for each car. Then, optimizers for the different parts of the track are presented; this allows the cars to be optimized for any track they may race on. Finally, splitting off the straightaway optimizer are the acceleration and braking optimizers, which inform the designer of the last possible second the driver needs to brake and how hard they need to brake in order to get the best performance from turn to turn.

There was little mathematical support for the selection of reconfigurable components from the three cars. They did some work to determine that it would be feasible to make the airfoils reconfigurable. However, the selection of the specific reconfigurable airfoils showed no mathematical support. For the team's third vehicle, none of the airfoils were made fully reconfigurable. Instead, only the angle of the airfoils were made reconfigurable. Then, for the second vehicle, four airfoils were selected to be fully reconfigurable. Finally, for the number one car, eight of the airfoils were made fully reconfigurable.

2.4.5 Linear State-Feedback Control

Many reconfigurable designs exist, but one major problem is how to get from one optimal configuration to the next when the requirements or environment changes. Ferguson and Lewis [63] have devised a solution using linear state-feedback control. Currently, an aircraft can only extend or retract wing flaps during takeoff and landing to change the wing's area, while the morphing wing can change almost any aspect of itself. The morphing wing will change aspects, such as airfoil shape or wing cross section, to maintain optimal performance. However, the process of changing from one optimal configuration to the next does not occur instantaneously. Because the manner of reconfiguration has a direct impact on performance and time required for each modification to be completed, the path chosen when varying configurations becomes vital. The path constructed between the two end points must take into account both the efficiency of the path and the constraints on the entire system [63]. Although the most direct path is a vector between the two end configurations, there is a possibility of violating some system constraint or losing stability of the system. Ferguson and Lewis discovered that changing in the way predicted by the Pareto frontier does not always result in the optimal path. As an alternative solution, they have presented the following suboptimization problem:

Minimize

$$F_j(x) + \sum_{i=1}^{n}(x_i^q - x_i^B)^2 \tag{2.9}$$

subject to

$$(x_i^q - \Delta x_i) \leq x_i^q \leq (x_i^q + \Delta x_i) \qquad \text{for i = 1 \dots n} \tag{2.10}$$

$$x_i^L \leq x_i \leq x_i^L \qquad \text{for i = 1 \dots n} \tag{2.11}$$

$$g_k \leq 0 \qquad \text{for k = 1 ... m} \tag{2.12}$$

Equation 2.9 is comprised of two parts: the part of the problem that is to be minimized and the distance from the current design point to the end point. Equation 2.10 establishes the boundary of the hyperbox. Equation 2.11 considers the constraints on the entire system [63]. The suboptimization problem places a hyperbox around the current design in the design space and searches for a location within the box that gives the most optimal solution. It then continues with this pattern until it reaches the final destination. The larger the hyperbox the faster the final solution is obtained. However, when the size of the hyperbox is altered the optimal path also changes. Therefore, there is a tradeoff between speed of transformation and optimality of the path.

2.5 Chapter Summary

Much of the work that has been performed in the area of reconfigurability and several related fields have been presented in this chapter. Reconfigurable systems are a subset of several fields, including flexible systems, changeable systems, and transformers. The growth of reconfigurability has led to the development of methods for the design of reconfigurable systems, as well as the research and development of several reconfigurable systems. The following chapters will use much of this work as a basis for the study of a large sample of reconfigurable products.

CHAPTER III

STUDY OF RECONFIGURABLE PRODUCTS

Reconfigurability is an established strategy for meeting diverse needs with a single product. This chapter will present a sample of reconfigurable products that were studied to search for distinguishing characteristics and patterns that these products employ to aid designers in the development of new reconfigurable products. In the following sections, the reconfigurable products will be broken down based on several categories: area of reconfigurability, reconfiguration process utilized, incorporation of adjustability and sizing, number of configurations, and size of the product.

3.1 Identification of Reconfigurable Products

To perform a study of reconfigurable products, a representative sample of reconfigurable products was needed. Several different approaches have been used in the past to produce a sample of representative products. A small sample of six products was developed for a flexibility study by using brainstorming and narrowing by product complexity [65]. Another sample of flexible products was developed by using an inductive direct patent study and empirical product study [66]. A large sample of transforming products was developed using both an inductive and deductive approach [76]. The inductive approach searched for natural analogies, existing products, and patents using keywords. The deductive approach looked at situations and scenarios in which they believed required the need for a transformer. Another method was the utilization of papers with example products, books illustrating design principles, observation, and internet searches [79].

The approach used to find reconfigurable products for this paper, was very similar to the approach used by Weaver et al. [79]. For this research, reconfigurable products were found by reading papers on reconfigurability and parallel fields [61, 69, 70, 73, 75, 76, 79], studying products from everyday life, and by conducting an internet search with keywords often used to describe reconfigurable products. Some of the words commonly used include: reconfigurable, flexible, transforming, convertible, adjustable, adaptable, expandable, extendable, morphing, interchangeable, -in-1, modular, "Grow with Me", and retractable. The search included available products, conceptual products, and patents. Also, if a reconfigurable product was found and it was discovered that there were comparable products with similar capabilities and functions, only one of these products was added to the sample. This allowed for a broader range of samples. After a thorough search was performed, a list of 90 reconfigurable products was generated. A complete detailed list can be found in Appendix A. These are, by no means, all the reconfigurable products available in the market or in the development process. These 90 products simply provide a representation of the many different types of reconfigurable products.

3.2 Reconfigurability Areas

After studying several reconfigurable products, it was realized that there are distinct areas where reconfigurability was applied to products. Eight areas in total were identified. The first seven of these areas describe the dedicated products that are being combined into the reconfigurable product and the last area describes the reconfigurable product itself. The eight areas are:

1. *One product used for two different purposes*

   Products that fit under Area 1 take advantage of the methods in which people already interact with products. This area studies how individuals use products in ways they were not designed or intended to be used. For example, when a bed is not available, an individual will oftentimes use a sofa as a place to sleep. Therefore, there is one product, a sofa, being used for two different purposes, as a sofa and as a bed. The product becomes reconfigurable when the two aspects are combined into the sleeper sofa, pictured in Figure 3.1. The sleeper sofa can be used as a sofa during the day and at night the concealed mattress can be taken out making a bed.

Figure 3.1: A sofa that is able to reconfigure into a bed to fulfill two different requirements [6].

2. *Similar products designed toward different market segments*

   When designing a new product, designers must be certain they fit the product to their intended market segment. If they fail to do this, there is a greatly reduced chance of product success. Making a product reconfigurable across more than one market segment has the ability to attract a larger audience or extend a product's use cycle. The Little Leaps Grow-with-me Learning System, pictured in Figure 3.2, is an example of an Area 2 reconfigurable product. The designers have extended the product's use cycle by designing one configuration for use by infants age 9 to 24 months, while the other for toddlers age 24 to 36 months.

Figure 3.2: A controller with each configuration designed for use by a different age range: 9 to 24 months and 24 to 36 months [7].

3. *Same product, different sizes to accommodate different portions of the population*

   Since everyone's body dimensions and preferences vary, often a product must be designed with different sizes in order to accommodate these variations. Products under reconfigurability Area 3 combine these different sizes into one product, allowing for a wider range of accommodation with a single product. Frequently, by doing this, sizes that were not available with the dedicated products become available with the reconfigurable product, providing even better accommodation;

the ability of a user to use or fit a product or environment as desired. For example, the Accu-Length Expandable Junior Golf Club, pictured in Figure 3.3, allows for the addition of inserts to extend the shaft length, meaning a new set of clubs will not have to purchased every time the junior golfer grows a few inches. Also, the inserts are small enough that they provide shaft lengths that would be not available with normal dedicated junior golf clubs.

Figure 3.3: A golf club that is able to accommodate different portions of the population with the use of inserts to adjust shaft length [8].

4. *Same product, different sizes to accommodate different numbers of people*

   Designers will ordinarily provide products with different sizes to accommodate different numbers of people in hopes of meeting the needs of a wide range of consumers. What a consumer purchases is frequently dependent on family size; they want a product that is able to fit their entire family. However, especially in young families, the family size can quickly change and they may be required to purchase new products to accommodate the growth. Reconfigurable products under this area provide users with a solution. One example is DB Fletcher's Capstan Table, shown in Figure 3.4. The table is able to reconfigure between two table sizes with an expansion ratio of 73% from small to large.

5. *Similar products that perform different tasks*

   Different tasks generally require distinct products in order to complete the task optimally. For example, the multi-head hammer pictured in Figure 3.5, each head

Figure 3.4: The Capstan table that is able to expand and contract to provide two table sizes [3].

has a different hardness, making each head ideal for different tasks. The softer heads can be used on tasks where it is important that the surface does not get scratched and the harder heads can be used on harder nails that the softer heads would not be able to handle. This area takes these products that are similar in nature and combines them into one reconfigurable product.

Figure 3.5: A hammer with multiple, interchangeable heads of varying hardness to be used for different tasks [9].

6. *Same product, different variations to be used in different environments*

   Frequently a particular product is required depending on the type of environment, whether it be inside/outside, day/night, sunny/cloudy, wet/dry, etc. Since the core structure is generally identical and only slight variations between products are required, products described by Area 6 are often combined or made reconfigurable. An example product is Michelin's E.A.P. concept tires pictured in Figure 3.6. The tires will combine the benefits of all-weather tires with snow tires without the need to switch tires at the beginning and end of every winter. They will use electroactive polymers, also known as artificial muscles, to change tread shape and depth depending on road conditions. The tires will be able to achieve configurations for dry, low rolling resistance, wet, and snow conditions [10].

Figure 3.6: Michelin's E.A.P. concept tires that can change tread pattern and depth for varying road conditions [10].

7. *Same product, different variations for consumer appeal*

   People have differing opinions of what looks good and what does not. This is one reason clothes are provided in different colors and patterns, bookshelves are made of different wood types with different stains, etc. Reconfigurable products under this area allow the user to configure the products to look exactly the way they would like. Nike's Energy Cheer Shoes, shown in Figure 3.7, are an example of an Area 7 product. The design provides the user with the ability to change the color of the swoosh symbol as often as desired.

Figure 3.7: A Nike shoe that provides the user with the option of changing the color of the swoosh symbol [11].

8. *Product is reconfigurable for storage or transport purposes*

   All other areas have focused on combining varying products into one reconfigurable product. This area, on the other hand, looks at taking a dedicated product and collapsing it for storage or transport. For example, an individual living in a small apartment must make the most of the space they have. In order to do this, products they purchase are often foldable or collapsable, so they can be hidden when not in use. A product that fits under this area is the murphy bed, shown in Figure 3.8. At night the user has a normal bed and during the day it can be folded away to leave more open floor space.

Figure 3.8: A bed that is able to be folding up into the wall to provide more open floor space [12].

A table containing the 90 reconfigurable products separated into their designated areas can be found in Appendix A. The products were selected in order to have at least five products in any given area. This ensures that each area is represented by the reconfigurable products it can provide. Some areas have several more products than others. This was a result of the types of products found while searching. The areas with more products appear to be more open to the use of reconfigurability in the design phase, or reconfigurability may be easier to apply to the products.

It is important to note that even if a group of dedicated products fits into one of these first seven categories, it does not mean that they should be combined into a reconfigurable product. There are other important aspects that need to be examined besides which area they fit, such as the connection of the functionality to the core structure of the product.

3.3 Means of Reconfiguration

As mentioned in Section 2.2.1, many processes utilized to get from one configuration to another have already been identified with the transformation principles. However, prior to studying the field of transformation, the sample of 90 reconfigurable products used in this paper was studied and segmented to identify ways in which reconfigurable product reconfigure. Therefore, in this section, the methods identified in the field of transformation and for this research will be compared with one another to ensure a complete list.

From the sample, each product was looked at individually to determine what process was used by the product to obtain each of its configurations. These processes are called the product's *means of reconfiguration*. After determining a means of reconfiguration for each product, it was discovered that there were four types:

- Modular
- Expansion/compression
- Reorientation
- Concealment

Products utilizing *modularity* as their means of reconfiguration contain similar parts where one can simply be substituted for another based on the customer's needs at a given time. An example of a modular product is multi-lens eyewear, as seen in Figure 3.9(a). The user is able to change the glasses' lenses to ideally match the correct type of environment or activity in which they are involved.

Expansion/compression describes products that are able to have the dimension of one or more of its attributes made larger or smaller depending on customer needs. One key element about expansion/compression is that it must be built into the product. In other words, no material should be added or removed in order to change the dimension of the product attribute. Crutches are an example of a product with this means of reconfiguration and shown in Figure 3.9(b). With crutches, the user is able to adjust the crutch height to best match their stature without adding or removing any material to or from the crutch.

Products using *reorientation* create a new configuration by reorienting some aspect of the product. The new configuration generally has the same basic overall function as the other configuration; it just has a new look or feel. However, it is not required that the configurations provide the same overall function, it is just more common. Reorientation may be understood with an example. One product that incorporates reorientation is shown in Figure 3.9(c), the Boon Benders Adaptable Utensil. This utensil is designed for use by toddlers and has a flexible neck. The parent can adjust the angle of the neck to be most comfortable for their toddler to use while eating. So, the utensil has the same function, picking up food, but the neck is at a different angle.

Concealment describes a product that provides an obvious function, but there is also a hidden element to the product that provides its own separate function. An example of this means of reconfiguration is a sleeper sofa, as pictured in Figure 3.9(d). The sleeper sofa has the obvious function as a sofa, but also contains a hidden element of a bed.

(a) modular (b) expand/compress (c) reorientation (d) concealment

Figure 3.9: Examples products representing the four means of reconfiguration: modular, expansion/compression, reorientation, and concealment [13, 14, 15, 6].

To simplify, the means of reconfiguration data was compressed into two categories. These two categories were taken from Siddiqi's three fundamental processes of reconfiguration: addition, subtraction, and transposition [74]. For the purposes of this paper, however, addition and subtraction were combined into one category, addition/subtraction. If flexible systems were the focus, having two separate processes would be logical, since a flexible system cannot be reversed once it has taken a new configuration. However, reconfigurable systems can be changed repeatedly and reversibly. Therefore, if a product undergoes some form of addition, it will have to undergo subtraction in order to return to the previous state. If a product is not undergoing addition or subtraction, then it must undergo transposition in order to obtain a new configuration. A product utilizing transposition uses its already existing components and rearranges them to create a new configuration [74]. Once the two fundamental processes of reconfiguration were decided upon, it was noticed that two of the four means of reconfiguration fit under the two fundamental processes of reconfiguration. Table 3.1 shows this pairing.

Modular was included under addition/subtraction because in order for a modular product to change configurations, a module must be added, removed, or substituted for another module. Expansion/compression was placed under addition/subtraction since when a product is being expanded or compressed, some feature must be added or subtracted in order to give a new configuration. Reorientation and concealment were placed under transposition because these means of reconfiguration use the already existing components of the product to create their different configurations. The four means of reconfiguration and fundamental processes of reconfiguration were placed into Table 3.2 to see if the reconfigurability areas had any affect. The numbers in the table represent the number of products in the sample under each heading.

There were very few distinguishing patterns present between the means of

Table 3.1: Pair of the fundamental processes of reconfiguration with the four means of reconfiguration.

Fundamental Processes of Reconfiguration	**Means of Reconfiguration**
Addition/Subtraction	Expansion/Compression Modular
Transposition	Reorientation Concealment

Table 3.2: Area-by-area summary of the mean of reconfiguration and fundamental process of reconfiguration utilized by each product.

	Conceal	Reorient	Modular	Expand/Compress	Add/Subtract	Transpose
Area 1	6	1	-	-	-	7
Area 2	6	7	4	6	10	13
Area 3	-	1	1	8	9	1
Area 4	-	1	2	2	4	1
Area 5	2	3	6	-	6	5
Area 6	5	6	4	3	7	11
Area 7	-	-	5	-	5	-
Area 8	6	2	-	3	3	8

reconfiguration data and reconfigurability areas. One thing that was noticed was that Area 7, same product, different variations for consumer appeal, contained only modular means of reconfiguration. Since the consumer appeal is being altered in Area 7, generally, the only way to achieve this is to remove some aspect and replace it with another. Another observation was that Area 1, people use one product for two different purposes, contains only products that use transposition. Again, this seems logical since, in this area, one product with a certain function is being reconfigured into another product with a completely different function.

3.3.1 Comparison of the Means of Reconfiguration with the Transformation Principles

As mentioned in Section 2.2.1, reconfigurable systems and transformers are analogous. Therefore, the transformation principles identified by Singh et al. and the means of reconfiguration should be comparable. Nevertheless, one major difference was discovered. When their research was completed, three transformation principles were identified: expand/collapse, expose/cover, and fuse/divide. On the other hand, in this paper, four means of reconfiguration were identified: modular, expansion/compression, reorientation, and concealment. Overall, the definitions match up well; Table 3.3 provides a breakdown of the pairing. Nevertheless, reorientation has no transformation principle counterpart and does not fit within any of the other categories.

It is unclear why reorientation or some other related concept was not included in the transformation principles. The authors may not have studied any products with this method of transformation or it may have been overlooked. The next section will present reorientation and products using this mean of reconfiguration in more depth.

3.3.2 Products Unrepresented by Transformation Principles

Of the 90 products studied for this paper, 21 contained reorientation as their means of reconfiguration. When these 21 products were examined more closely, it was discovered that even though reorientation does not match up well with any of Singh et al.'s transformation principles, a few of these products using reorientation fit under the transformation principle of expand/collapse. The reason this is possible is due to the fact that there is a slight variance in the definition provided for transformation principle expand/collapse and the definition used for the mean of reconfiguration expansion/compression. Expand/collapse describes an increase/decrease in occupied volume along an axis, in a plane, or in three dimensions, while expansion/compression describes simply having the dimension of one or more of its attributes increased/decreased. A folding ping pong table is an example of one of these products. This being the case, of the 21 product that contain reorientation as their means of reconfiguration, 9 fit under the transformation principle of expand/collapse, while 12 still do not fit under any transformation principle.

A short description of the methods used by these 12 products to obtain different configurations is provided below. By explaining how these products reconfigure themselves, it will prove that these products, indeed, do not fit under any of the three transformation principles.

Little Tikes 5-in-1 Adjustable Gym

The Little Tikes Adjustable Gym utilizes the "Grow with Me" theme presented with many infant and toddler toys; each of the 5 configurations of the gym accommodates

Table 3.3: Pairing of transformation principles and means of reconfiguration.

Transformation Principle	Mean of Reconfiguration
expand/collapse increase/decrease in occupied volume along an axis, in a plane, or in three dimensions	**expansion/compression** built-in change in dimension of one or more product attributes depending on customer needs
expose/cover revealing or concealing a new surface to alter functionality	**concealment** product with an obvious function, as well as, a hidden element that produces its own separate function
fuse/divide making a single functional device become two or more devices, at least one of which has its own distinct functionality defined by the state of the transformer	**modular** product with similar parts, where one can be substituted for another based on the customers needs
	reorientation create a new configuration by reorienting an aspect of the product to provide a new look or feel

a different age range. The traditional play gym is shown in Figure 3.10(a), and Figure 3.10(b) shows the seated activity center configuration. The differences between these two configurations are the angles of the top activity piece and bottom green piece. The top activity piece is able to rotate and lock into 12 positions, while the bottom green piece rotates from a kickpad to a seat [16].

(a) (b)

Figure 3.10: Pictures depicting the traditional play gym and seated activity center configurations of the Little Tikes 5-in-1 Gym achieved by reorienting the top activity piece and bottom green piece [16, 17].

Snowboard bindings

Snowboard bindings provide the user with different angle options in order to match their preferred stance. To change the angle, the user loosens the binding from the board, rotates the outside piece to their desired angle, and retightens the binding to the board. Two binding angles are shown in Figure 3.11.

(a) (b)

Figure 3.11: Two possible configurations of a snowboard binding obtained by rotating the binding about the axis of the board.

Bell-Boeing V-22 Osprey

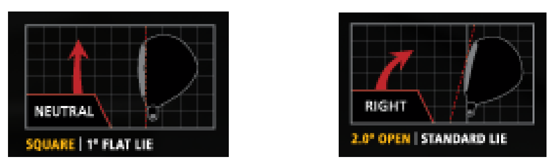
The V-22 Osprey is a multi-mission aircraft designed for military use. It combines the conventional performance of a helicopter with the long-range, high-speed cruise performance of a turboprop aircraft [53]. The configurations differ by the angle of the nacelles. When the nacelles are at 0°, as in Figure 3.12(a), the aircraft is in airplane mode and when the nacelles are at 90°, as in Figure 3.12(b), the aircraft is in helicopter mode. To get from one configuration to the next the nacelles can rotate in as little as 12 seconds [53].

(a) (b)

Figure 3.12: Depiction of the rotation of the Osprey's nacelles to achieve airplane and helicopter configurations [18, 19].

Taylor Made R9 Driver

Taylor Made implements Flight Control Technology (FCT) and Movable Weight Technology (MWT) to achieve several different configurations in their R9 driver. FCT allows the user to adjust the loft, lie, and face angle by rotating a sleeve on the tip of the shaft which, in turn, adjusts the characteristics of the head. Figures 3.13 (a) and (b) illustrate two different configurations using FCT. MWT allows the user to change the center of gravity location of the club. To do this the user moves differently weighted cartridges in ports on the club head [20].



(a) (b)

Figure 3.13: Two FCT configurations of the R9 driver produced by rotating the club head to obtain a square and a open face [20].

Reconfigurable Race Car

The reconfigurable race car is a conceptual car. It is used as an example in a few papers about reconfigurability and flexibility [61, 60, 71]. A component of the car that does not fit under one of the transformation principles is the movable center of mass. The concept is to have the center of mass shift depending on the track to allow the driver to take turns faster and thus reduce laps times.

Hospital beds

Hospital beds allow for the angles of the head and foot of the bed to be adjusted to match the user's needs. The head of the bed can generally be angled anywhere from 0° to 75°, while the foot can be adjusted from 0° to 45° [54]. Figure 3.14 shows two possible angles for the head of the bed.

(a) (b)

Figure 3.14: A hospital bed in two different configurations achieved by adjusting the angle of the head of the bed [21, 22].

Coach Penelope OP Art Purse/Wristlet

The Coach purse/wristlet provides the user with the choice of either a purse or a wristlet. To change between configurations, the strap of the bag is changed. For a purse, the strap is placed such that each end is located on an opposite side of the bag, as seen in Figure 3.15(a). To obtain a wristlet, the strap is unhitched from one side and reattached such that both sides of the strap are located on the same end of the bag, as seen in Figure 3.15(b).

(a) (b)

Figure 3.15: Purse and wristlet configurations of a Coach bag obtained through the reconfiguration of the bag's strap.

Divnick All-in-one Golf Club

The Divnick all-in-one golf club provides the user with 34 clubs in 1: putter, driver, a full set of irons, and 8 wedges. The club is able to achieve this by rotating the head of the club to adjust the loft, with each loft pertaining to a different club. To adjust the loft, the user loosens the black lever, rotates the head until the arrow matches the desired loft, and retightens the black lever [23]. Figure 3.16(a) shows a picture of the club head, while Figure 3.16(b) shows a close up of the adjustment mechanism.

(a) (b)

Figure 3.16: Divnick all-in-one golf club head and adjustment mechanism used to obtain varying face angles through the rotation of the club head [23].

Boon Benders Adaptable Utensils

The Boon Benders Adaptable Utensils are designed for use by toddlers with developing motor skills. The utensil has a flexible neck allowing the parents to adjust the neck to an angle that is most comfortable for their toddler to use while eating. As the child's motor skills develop, the angle of the neck become straighter [15]. Figure 3.17(a) shows the utensils with a straight neck and Figure 3.17(b) shows some with an angled neck.

(a) (b)

Figure 3.17: Adaptable utensils straight and angled neck configurations obtained by folding the neck to the desired angle [24, 15].

Appliance doors

Appliances, such as refrigerators, are designed in a way that makes it is possible to change the direction in which the doors open. To reverse the direction the door opens, both the handles and the hinges must be removed and placed on the other side of the door.

Ping Pong Door

Tobias Fränzel's ping pong door was mainly designed for space saving purposes. It has two possible configurations: a door, as seen in Figure 3.18(a), and a ping pong table, as seen in Figure 3.18(b). To get from one configuration to the other, the table is rotated about a pivot in the middle of the door.

(a) (b)

Figure 3.18: Door and table configurations of the Ping Pong Door achieved by rotating the table about a pivot in the middle of the door [25].

Convertible Hand Truck

The convertible hand truck has two possible configurations: a two wheeled hand truck, pictured at Figure 3.19(a), and a four wheeled hand truck, pictured in Figure 3.19(b). To get from configuration (a) to configuration (b), the handle of the hand truck is unlocked, extended, and rotated into the new position.

(a) (b)

Figure 3.19: Two and four wheel configurations of a hand truck obtained through the reorientation of the handle [26].

The descriptions provided for these 12 products show that expand/compress, fuse/divide, and expose/cover do not describe the reconfiguration processes utilized by these products. There is an additional area needed to describe their reconfiguration process that was overlooked by Singh et al. during the defining of the transformation principles. Since the transformation principles are incomplete, the four means of reconfiguration have been proven to better represent the reconfiguration methods used by products with multiple configurations.

3.4 Reconfigurability Needs

All 90 reconfigurable products were studied to determine whether or not they contained one or more of the three main needs addressed by reconfigurable products: multi-ability, evolvability, and survivability. When determining which products contained these needs, the definitions provided by Siddiqi [74] were used. These definitions are:

1. **Multi-ability:** property in which a system can perform multiple, distinctly different forms or functions at different times

2. **Evolvability:** property that allows a system to change easily over time by removing, substituting, and adding new elements and/or functions

3. **Survivability:** property that allows a system to remain functional, possibly in a degraded state, despite a few failures

In the complete sample, 90 contained multi-ability, 22 contained evolvability, and 40 contained survivability. All products contained multi-ability since each product contains varying configurations that provide something distinctly different from the product's other configurations. After examining all three properties together, it was noticed that 22 products contained all of them. These 22 products that contain multi-ability, evolvability, and survivability all reconfigured by means of modularity. It was also noticed that all the modular products were the only products that contained evolvability. It seems as though modularity and evolvability go hand-in-hand with reconfigurable products. It also explains why all the modular products were also survivable; if one module breaks it can simply be replaced by another module. Also, examining products that used expansion/compression as their means of reconfiguration, only two of the 15 products contained survivability. This led to a more in depth look at non-modular survivable products. It appears as though if the reconfigurable aspect is not connected to the overall function of the product, then the product will be survivable. An adjustable computer chair provides an example of this. If one of the adjustable aspects of the chair should break, the chair would still be able to be used for seating. The only difference is that it cannot be adjusted. Furthermore, if the reconfigurable aspect is connected to the overall functionality of the product, it could still remain survivable, as long as more than one unconnected option is available. For example, the reconfigurable aspect of the ballpoint and ink provide the functionality of multi-ink pens. However, if one of the ballpoints should malfunction, other color options are still available for use.

There were a few other interesting observations pertaining to the reconfigurable areas. The first observation was that all seven products in Area 5, similar products that perform different tasks, contained survivability. This seems to be since, for the products in this area, each configuration performs a different unrelated task. Therefore, if one configuration is not functioning, the other configurations should still be able to maintain some type of functionality. The other observation was that all of the products in Area 1, people use one product for two different purposes, were neither evolvable nor survivable. In Area 1 the use of each configuration depends on the other configurations. Therefore, this must also be a key factor in determining whether a product is evolvable and/or survivable.

3.5 Adjustability and Sizing

Each of the reconfigurable products was carefully examined to determine if it contained any adjustability and/or sizing. A product is considered to contain adjustability if it is able to change the dimension of one or more its attributes. Unlike expansion/compression discussed with the means of reconfiguration, adding or removing material in order to change the dimension of the product's attribute can achieve adjustability. A product with sizing contains different sizes of the same product. These categories were broken down to determine whether or not the adjustability and/or sizing were incorporated into the design as a means of accommodating human variability; human variability is the inherent variability in aspects such as stature, BMI, strength, etc. that exists in the human population. Figure 3.20 provides examples for each of these four categories.

(a) adjustable (b) adjustable for human variability (c) sizes (d) sizes for human variability

Figure 3.20: Examples of products with adjustability, adjustability for human variability, sizes, and sizes for human variability [27, 28, 3, 29].

Figure 3.20(a) is the Taylor Made R9 driver. This driver is adjustable in face angle, loft, lie, and center of gravity to match the golfer's specific needs on the course. Figure 3.20(b) is the Herman Miller Mirra chair. The chair contains adjustable elements such as seat height, lumbar support, seat pan depth, and arm rest height to accommodate a wide range of the population. The DB Fletcher Capstan table is shown in Figure 3.20(c). This table provides three different sizes: 80 to 105 inches, 75 to 98 inches, and 69 to 91 inches. Finally, Figure 3.20(d) is a pair of Adidas Excel 1C baseball cleats. These cleats, as well as any type of shoe, accounts for human variability by providing different sizes to accommodate different feet lengths and widths. Table 3.4 provides an area-by-area breakdown of adjustability and sizing for all 90 reconfigurable products. In the table, (A) is Adjustability, (AHV) is Adjustable for Human Variability, (S) is Sizes, (SHV) is Sizes for Human Variability, and the final four columns are combinations of the first four. The numbers in the table represent the number of products in the sample under each heading.

A breakdown of Table 3.4 shows several things. First, 35 products contained adjustability, 30 contained sizes, and 30 products contain sizes and/or adjustability relating to human variability. However, of these 30 containing sizing and/or adjustability for human variability, only 5 contain both sizing for human variability and adjustability for human variability. This shows that the pairing of adjustable for human variability and sizes for human variability is not present or is of little importance in a significant number of reconfigurable products. However, these five products with AHV/SHV were all located under Area 3. This seems logical considering Area 3 is for products with different sizes to accommodate different portions of the population. In addition, all products in Area 3 contain adjustability for human variability. Second, it is uncommon for a product to be adjustable in one aspect and have sizes pertaining to human variability in another aspect. There was only one product like this in the group of 90 studied. This product was the Taylor Made R9 Driver. The driver is adjustable in face angle, loft, lie, and center of gravity. However, it provides sizes for right handed individuals or left handed individuals, as well as different shaft stiffnesses.

3.5.1 Adjustable for Human Variability

Of the 90 reconfigurable products studied, 21 contained adjustability for human variability. Of these 21 products, 10 were designed for the developing/growing child, which is a significant portion of the products. Since children grow and develop quickly, it seems logical to incorporate adjustability to accommodate this rapid growth. Parents do not want to have to purchase a new product every time their child ages a few months or grows a few inches. Reconfigurability allows the product to grow with the child and, thereby, increases the life of a product. Instead of having to purchase a new product as their child grows or develops, the parent can reconfigure the product to create a new configuration that better accommodates their child.

When studying the products that are adjustable for human variability, it was noticed that there were five reasons that a product would be reconfigurable to accommodate

Table 3.4: Area-by-area summary of product adjustability and sizing. The numbers in parenthesizes are the total number or products in the given areas.

	A	AHV	S	SHV	A/S	AHV/S	A/SHV	AHV/SHV
Area 1 : (7)	-	-	4	1	-	-	-	-
Area 2 : (23)	13	8	5	1	3	1	-	-
Area 3 : (10)	10	10	5	5	-	-	-	5
Area 4 : (5)	2	2	3	-	-	2	-	-
Area 5 : (11)	3	-	2	1	-	-	-	-
Area 6 : (18)	5	-	7	5	-	-	1	-
Area 7 : (5)	2	1	1	1	-	-	-	-
Area 8 : (11)	-	-	3	-	-	-	-	-

human variability:

- Anthropometry
- Motor skills
- Attention span
- Strength
- Skill level

The most common of these reasons is anthropometry. Everyone is different and a designer must incorporate these variations into their design if they want the product to accommodate a wide range of individuals. The kid's adjustable skates, pictured in Figure 3.21(a), provide an extendable base to accommodate a range of four shoe sizes.

As a child grows, both their fine and gross motor skills develop. An example of a product that accommodates different levels of motor skills is the Little Leaps Grow-with-me Learning System, pictured in Figure 3.21(b). The first configuration is designed for use by infants age 9 to 24 months. This configuration contains buttons of different shapes and colors that can easily be pressed by infants. The other configuration is designed for use by toddlers age 24 to 36 months. This configuration contains both buttons and a joystick for the toddler to control.

As children grow, so to do their attention spans. Hasbro has incorporated this variability into their Candy Land Sweet Celebration board game. The game allows the user to control the length of the playing board and, therefore, the duration of the game. As a child's attention span grows, additional pieces can be added to make the playing board longer. One configuration of the game is pictured in Figure 3.21(c).

People also vary in terms of strength. The stronger an individual, the more weight they will be able to handle. The Reebok dumbbells pictured in Figure 3.21(d) allow the user to adjust the weight of the dumbbell in specified increments to match their weight need.

Ski bindings, pictured in Figure 3.21(e), are an example of a product that is adjustable for human variability to accommodate varying skill levels. The bindings also

(a) anthropometry

(b) motor skills

(c) attention span

(d) strength

(e) skill level

Figure 3.21: Example products representing five reasons for incorporating adjustability for human variability [30, 7, 31, 32, 33].

accommodate variations in stature, weight, and foot length. The user gives their height, weight, boot sole length, and skill level to a technician who adjusts the binding's DIN number to the appropriate release tension. The DIN number controls how easily the bindings release the boot during a fall. Therefore, the more advanced the skier, the higher the release tension, and the higher the DIN number.

All four means of reconfiguration were also utilized in obtaining adjustability for human variability. The Accu-Length Expandable Golf Clubs, pictured in Figure 3.22(a), use modular inserts to adjust the club's shaft length to accommodate varying statures. Crutches, as shown in Figure 3.22(b), accommodate different statures through the use of extend/compress. To move between configurations, the base of the crutch is extended out of or compressed into the rest of the crutch's structure. The Little Tikes 5-in-1 adjustable gym pictured in Figure 3.22(c) accommodates developing motor skills by providing different configurations for different age ranges. The different configurations can be achieved by rotating the top activity piece and the bottom green piece. An example of concealment is shown with the Little Leaps Grow-with-me Learning System, pictured in Figure 3.22(d). As mentioned previously, the product accommodates different motor skill levels with each of its configurations. To get from one configuration to the other the

(a) modular (b) extend/compress (c) reorientation (d) concealment

Figure 3.22: Examples of products utilizing the four means of reconfiiguration to incorporate adjustability for human variability [8, 14, 16, 7].

interactive controller is flipped, concealing the unused side in the controller's base. Which means of reconfiguration is used greatly depends on the designer's design criteria.

3.6 Number of Configurations

Another important factor studied was the number of configurations provided by each product. This is an important factor because the designer must decide how many dedicated products should be combined into one reconfigurable product. If there are too few configurations, the product may not provide sufficient variety. Alternatively, if there are too many configurations, the product may become too complex. Therefore, the number of configurations is a critical feature.

Reconfigurable systems can exhibit either a unique configuration every time or be limited to a fixed set of distinct configurations [61]. For the reconfigurable products used in this paper, the number of configurations ranged from two to infinity. The products with infinite configurations were generally products that contained continuous adjustability. A product containing continuous adjustability can be adjusted to any desired dimension, generally within a set range. The number of configurations for the products in each reconfigurability area can be found in Figure 3.23. In this figure, the number of configurations was plotted on a log scale in order to better see the products with fewer configurations. Also, the products with infinite configurations are shown as having 10,000 configurations for simplicity.

When rearranging the products in order from lowest to highest number of

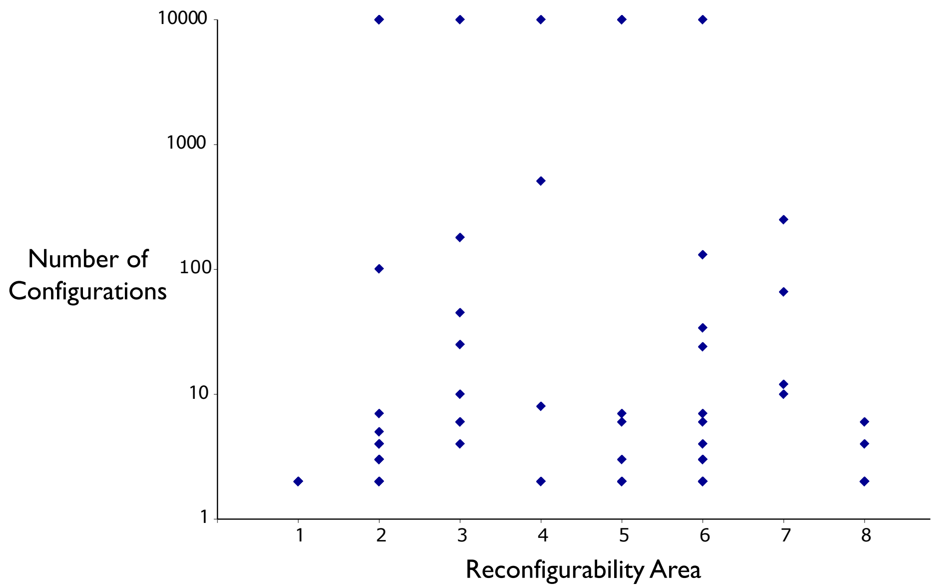


Figure 3.23: Number of configurations for each product broken down by reconfigurable area.

configurations, it was noticed that the majority of the products with only two configurations were reconfigured via transposition; of the 37 products with only two configurations, 33 used transposition.

When studying the number of configurations based on the means of reconfiguration used by the products, a general pattern was noticed:

- Concealment - fixed (few configurations)
- Modular - fixed (many configurations)
- Expansion/compression - fixed and unique
- Reorientation - fixed and unique

Each configuration supplied by products using concealment typically provide different functions. Combining of multiple functions into a single product is difficult. Therefore, these products are restricted to few configurations. Modular products, on the other hand, have the capability to provide many configurations through the mixing and matching of modules. However, even though the number of configurations can become extremely large depending on the number of modules, it is still a fixed set. Expansion/compression and reorientation have the capability to provide both a fixed set of distinct configurations or a unique configuration every time through the use of discrete or continuous adjustability. Products containing discrete adjustability provide a fixed set of adjustments, while products containing continuous adjustability can be adjusted to any desired dimension, generally within a set range.

Other observations were made based on the reconfigurability area in which the products are located. First, all Areas except for 3 and 7 have products with only two configurations. Area 3 contains products that accommodate different portions of the population. Therefore, if only two configurations were available, many sizes would be needed in order to accommodate a significant portion of the population. Second, Area 7 contains product variations for consumer appeal. All products in this area are modular. A modular product with only two configurations would not provide significant adjustment for the user. In the sample, all 22 modular products provided more than two configurations. Finally, all Areas except 1, 7, and 8 contained at least one product with infinite configurations. Area 1, people use one product for two different purposes, contains products in which each configuration provides a distinctly different function. If a product in Area 1 were to provide infinite configuration, it would have to provide infinite distinctly different functionalities. Area 7 contains only modular products and modular products are always confined to a fixed set of configurations. Area 8 contains products with a configuration for use and a configuration for storage. Again, providing infinite configurations here seems inefficient.

3.7 Product Size

One last feature that was studied was product size. The actual dimensions of the products were not used because many of the products are oddly shaped and obtaining actual product volume would be very difficult. Instead, the products were broken into three size groups:

- Small: glasses, shoes, backpacks, etc.
- Medium: chairs, sofas, tables, etc.
- Large: cars, planes, etc.

The sample contained 47 small products, 33 medium products, and 10 large products. However, these numbers greatly depend on how the cutoffs are made between the different sizes. Determination of the appropriate category for products like vacuum cleaners and crutches can be problematic. These products are much larger than many of the small products but also much smaller than some of the medium products. Classification of these borderline items can affect the number of items under each size.

Based on the division between sizes used in this paper, it seems as though smaller products are more easily made reconfigurable. This assumption is based on the fact that more than half of the reconfigurable products in this paper are small in size. Another observation was made studying the large products. Nine out of the ten large products reconfigured via transposition. The 10 large products consisted of three cars, three aircrafts, one car/aircraft, one machining product, and one structure. Of these, the only product that did not reconfigure via transposition was the machining product; it used modularity. Finally, examining adjustability and sizing, all five products with both adjustability for human variability and sizing for human variability are small products. Also, all products containing sizing for human variability are small products.

3.8 Chapter Summary

Reconfigurable products are everywhere, but they can be disguised behind many different names. Eight areas where reconfigurability has been applied to products have been identified. The majority of reconfigurable products are small and have only one reconfigurable attribute. A reconfigurable product will use one of four methods to reconfigure, not three as suggested with the transformation principles. For products that are larger, transposition appears to be the most suitable method of reconfiguration. A product has too many or too few configurations is non-optimal. Also, adjustability and sizing for human variability are not found in many of the products and it is rare to have a pairing of adjustability with sizing for human variability. Adjustability for human variability is incorporated into reconfigurable products for four main types of variability: anthropometry, motor skills, attention span, and skill level. Modularity and evolvability seem to go hand-in-hand in reconfigurable products. In addition, dependence of one configuration on another is an important factor in evolvability and survivability. This research is a starting point into the understanding of reconfigurable products. Much work still needs to be done to discover what makes certain products more successful than others.

3.9 Principle Contributions

Based on the analysis presented in this chapter, the principle contributions of this thesis are the following:

- Identification of areas in which reconfigurability is applied
- Evidence that the current list of three transformation principles does not represent the entire spectrum of reconfiguration processes utilized by products with multiple configurations
- Observation of the frequent use of transposition in products with two configurations
- Identification of five reasons for the incorporation of reconfigurability when accommodating human variability

As a whole, these contributions have the potential to greatly aid designers in the concept identification and generation of new reconfigurable products. Chapter IV will illustrate the use of these contributions through example products.

CHAPTER IV

APPLICATION OF FINDINGS

This chapter will apply the information that has been obtained while studying the reconfigurable products. Two sample products were used in hopes of creating new or improved reconfigurable products: baseball gloves and headphones. Since there are no reconfigurable baseball gloves on the market, the baseball glove was chosen in order to determine whether a reconfigurable product could be made in an area that relies heavily on dedicated products. On the other hand, headphones incorporate reconfigurability into several of the products. Therefore, headphones were chosen in order to improve upon the already existing reconfigurable products and perhaps generate new reconfigurable products should an opportunity be identified.

4.1 Baseball Glove

4.1.1 Variations

When looking for reconfigurability in a new product, the first step is to identify variations between similar products. For this, the reconfigurability areas presented in Section 3.2 were used. For example, reconfigurability Area 2 for the baseball glove is presented in Figure 4.1. The complete list with baseball glove variations in all reconfigurability areas can be found in Appendix B. These variations will later be used to help determine potential reconfigurability possibilities.

The majority of the variations between baseball gloves were found when studying the differences in the gloves between positions, since all baseball gloves are designed with one specific position in mind. These differences due to position are briefly described here.

Pitcher's gloves are typically 11 to 12 inches and have a closed webbing in order to

2. Similar products designed toward different market segments

baseball/softball	finger sleeve
righty/lefty	shallow/deep pocket
closed/open web	glove/mitt
closed/open back	leather quality

Figure 4.1: Baseball glove variations identified under reconfigurability Area 2.

hide the ball from the batter. Many also contain a finger sleeve for pitchers that raise their index finger when throwing a curveball.

Catchers and first basemen use a mitt instead of a glove, meaning the glove does not have any fingers. A catcher's mitt is shaped vary similar to a claw and contains a thick pad around the circumference of the mitt and thick padding in the palm and fingers for protection. A first baseman's mitt is typically 12 to 12.5 inches and contains a thin pad that runs around the circumference and little or no padding in the palm and fingers. The pad around the circumference of the mitt and the lack of fingers tend to do a better job of controlling balls that do not hit in the pocket.

An infielder will generally use a glove that is 11 to 12 inches. Middle infielders want a glove with a shallow pocket in order to be able to retrieve the ball from their glove more quickly. Because of this, middle infielders will typically use a glove with an open webbed design. A third baseman's glove tends to vary a bit depending on the player's style of playing. If they want to be able to get rid of the ball quickly, they will typically choose an open web design. On the other hand, if they want to make sure they secure the ball, since balls are hit to third base hard and frequently, they will tend to choose a closed web design. Infielders will also typically use an open back glove so it is not as stiff.

Outfielders will use gloves that are 12 to 13 inches in order to cover the most amount of ground possible. Although major league baseball rules clearly state that a glove cannot be longer than 12 inches [55], this rule is not strictly enforced and the majority of outfielders will use a larger glove. The glove will also have a deep pocket to secure the ball and typically have a closed back with a finger hole for added support [51]. Pictures of these different glove features are pictured in Figure 4.2.

Even though these guidelines are generally used by players, the biggest influence

(a) glove (b) mitt (c) closed web, closed back (d) open web, open back

Figure 4.2: Pictures depicting the distinctions between a glove and a mitt, open and closed webbing, and open and closed back [34, 35, 36, 37].

on which glove a player uses is preference. For example, the guideline says that middle infielders should use a glove with open webbing. However, Derek Jeter, a Gold Glove award winning shortstop, uses a glove with closed webbing.

Other variations were identified based on experience and observation. Another major variation between baseball gloves is due to a player's age. Youth gloves are designed with soft leather so they can be broken in easily and tend to have large pockets to help them catch the ball. The gloves are also designed with smaller finger and wrist openings to better fit a child's small hands. Table 4.1 provides guidelines for glove size depending on age and position.

4.1.2 Reconfigurable Possibilities

In general, the variations between baseball gloves are significant. Every variation has a distinct purpose and must be designed into the glove in order for the glove to provide the maximum performance. However, there did appear to be a few possibilities for

Table 4.1: Sizing guidelines dependent on age and position presented for the purchase of a baseball glove [51].

Age	Position	Glove Size
5-6	General	10-10.5 (youth model)
7-8	General	10.5-11 (youth model)
9-12	General	11-11.5 (youth model)
High School/Adult	Infield	11-11.5
High School/Adult	Outfield	12-12.5

reconfigurability. The basic equations presented in section 2.4.1 provide a method for choosing whether or not to make a group of dedicated products reconfigurable. However, as discussed, these equations do not take into consideration the importance of a product's capability. Therefore, this method was not used. Instead, the specific possibilities chosen were based on the identification of concepts. All variations presented in Appendix B were considered as potential reconfigurable possibilities. The four means of reconfiguration were used for concept generation and the three variations presented in this section provided solid concept ideas when working through the list of variations.

Youth gloves are the primary focus of the concepts presented in this section. This is because a little leaguer can easily use one glove to play any positions on the field, while in the Major Leagues it is vital that the glove be tailored to a specific position in order to provide the player with optimal results. Also, when a player is older, they tend to have one, maybe two, positions they always play. On the other hand, younger players tend to be moved around the field.

Youth Glove Size

Children grow rapidly and in order for a product to be able to be used by a single child over several years, the product must be designed accordingly. Nevertheless, every baseball glove is a dedicated design that offers little room for anthropometric growth. Parents may purchase a larger glove assuming their child will grow into it and it will last them longer. Unfortunately, if a glove is too large for a child's hand, it will typically fall off. This can lead to a child becoming annoyed and discouraged. Table 4.1 provides a table of recommended glove sizes for the different age ranges. However, this would suggest that a parent should purchase a new glove for their child every two years. That is a rather short life for a glove. A glove, when not used vigorously everyday, should last a player much longer.

The concept was to create a glove design that would be able to fit a child's hand for several years. When working through the four means of reconfiguration, the only mean that seemed able to accomplish this was expansion/compression. The concept would leave the basic structure of the glove the same in order to maintain the glove's capabilities.

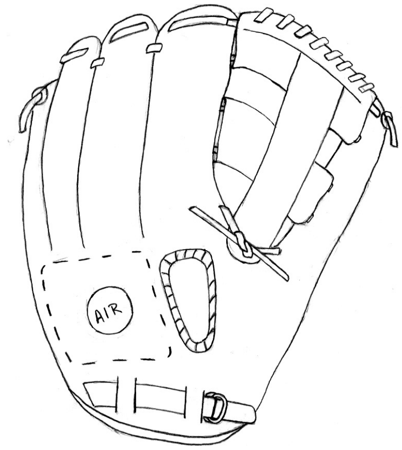


Figure 4.3: Concept drawing of the reconfigurable youth baseball glove with an inflatable air pocket to accommodate varying hand sizes.

The only difference would be the addition of an air pocket to change the amount of open space on the inside of the glove; it would be very similar to the Reebok Pumps. The air pocket would be located on the back side of the glove, pressing up against the back of the hand. A drawing of the concept is pictured in Figure 4.3. To incorporate the air pocket into the glove, the glove will have a closed back design; an open backed design would not have enough room for the air pocket. The air pocket should not go up the fingers of the glove because this would greatly increase the stiffness of the glove. The addition of the air pocket allows the user to adjust the glove to their specific hand size. The child would put their hand inside the glove and pump up the air pocket until their hand felt secure. This would allow for a child to play with the same glove for several years, even as their hand grows.

Shortstop/Pitcher

When younger, especially in little league, high school, and college, it is not uncommon for a team's shortstop to also be one of the team's pitchers. Shortstops tend to be very athletic and must have a strong arm to throw the ball across the field. This has the capability to transfer well to the pitcher's mound. However, as mentioned in the previous section, shortstops typically have a glove with an open web design, so they can retrieve the ball from their glove quickly, but pitchers typically have a closed web design, so they can hide

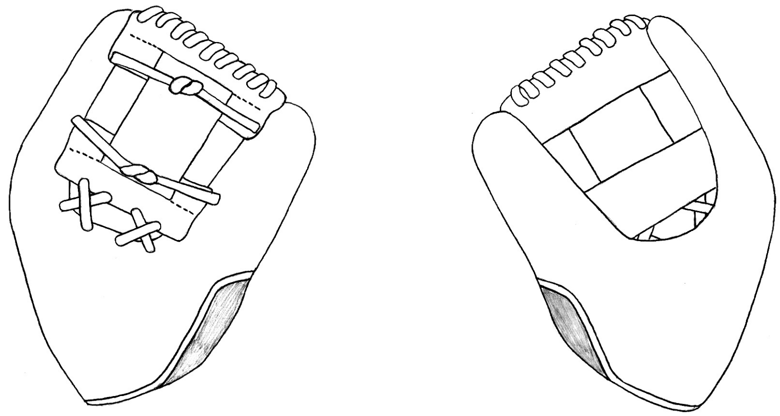
(a) Pro I (b) Pro H (c) Single Post (d) Modified Trapeze

Figure 4.4: Baseball gloves depicting the various open web designs used by infielders [38, 39, 40, 41].

the ball from the batter. Therefore, the player must have two separate gloves or make a compromise as to which aspect he considers to be more important. This reconfigurable concept aims to change that.

The webbing is a vital part of the glove and cannot be compromised. For this reason, transposition was not considered the best possibility, even though there are only two configurations. It is possible to change a glove's style of webbing if the holes on the glove match up with the openings in the new webbing. However, this does not occur often and switching a glove's webbing takes some time. Another viable option was discovered through reconfigurability with the use of modular design. The idea is to create an add-on that would cover the opening in the open web design. The attachment would need to be able to be attached and removed quickly, so the player can add or remove the attachment even in the middle of an inning. Therefore, the use of velcro was deemed a practical solution. To apply the attachment, the user would wrap velcro strips around the leather of the glove's web in several places to secure the attachment. Then to remove the web cover, they would simply undo the velcro.

There are four basic open web designs used by infielders: pro I, pro H, single post, and modified trapeze. Pictures of these web designs are shown in Figure 4.4. The webs vary greatly across the different designs. The only constant is a strap of leather running between the tips of the index finger and the thumb. Therefore, each webbing style needs its own web cover with its own distinct securing system layout. Also, as a glove's length changes, so too will the length of the web. Therefore, a different web cover will need to be provided for each length of glove manufactured.



(a) right handed (b) left handed

Figure 4.5: Concept drawings exhibiting the use of reorientation to achieve right handed and left handed configurations of a reconfigurable baseball glove.

Handedness

The concept presented here looks at a right-handed glove versus a left-handed glove. The gloves are almost identical, with the only difference being the orientation of the fingers and webbing. It is uncommon for a player to be ambidextrous, but combining a right-handed and left-handed baseball glove would be useful in an area such as a gym class, where the number of individuals who are right-handed or left-handed varies.

Since there are only two potential configurations, the use of transposition was considered first. The concept generated is fairly simple, to get from one configuration to the other the glove must be reoriented. Figure 4.5(a) shows the right handed configuration of the baseball glove. To get to the left-handed configuration, shown in Figure 4.5(b), the back of the right-handed glove is pushed through and becomes the inside of the left-handed glove. The same method is used to get from the left-handed glove back to the right-handed glove. The glove would need to be made of a soft leather to allow for sufficient material flexibility. Also, the shaded region in the pictures would be made of an elastic material, so as to make up for the difference in required amount of material from the back of the glove to the front of the glove. The glove would be required to have completely closed backs so that, depending on the configuration in use, the palm of the glove does not have any openings.

2. Similar products designed toward different market segments

over ear / on ear / in ear / ear bud
DJs / runners

Figure 4.6: Headphone variations identified under reconfigurability Area 2.

4.2 Headphones

4.2.1 Variations

Headphones come in a large variety of shapes and sizes. Therefore, the reconfigurability areas were used to aid in indentifying variations between the similar products. Reconfigurability Area 2 for headphones is shown in Figure 4.6, while all reconfigurability areas can be found in Appendix B.

The variations listed were identified from experience and research on the various types of headphones. There are four basic headphone types: over ear, on ear, in ear, and ear bud. An example of each type is presented in Figure 4.7. Each type provides its own advantages and disadvantages and the type an individual choses is generally based on listening style and preference.

Over ear headphones completely surround the ear and engulf the listener in sound. They come in closed back, open back, and noise canceling varieties. Closed back headphones are designed to isolate the listener from outside noise and, thereby, also prevent the music the user is listening to from escaping. Open back headphones do exactly the opposite. They allow the user to hear their surroundings and, in turn, the music being listened to may escape and be audible to nearby individuals. Noise canceling headphones cancel out surrounding ambient noise. They are often used when traveling on airplanes and trains.

On ear headphones come in various sizes and rest on top of the ear. They typically contain a headband that runs over the top of the head. However, there are clip on and behind the neck versions. On ear headphones are also available in closed back, open back, and noise canceling varieties.

In ear headphones are small and fit into and seal the ear canal, thus providing sound isolation. A user must find a size that will correctly fit your ear canal to provide the best

(a) over ear (b) on ear (c) in ear (d) ear buds

Figure 4.7: Product examples of the four distinct styles of headphones [42, 43, 44, 45].

seal.

Ear buds are typically provided with the purchase of any MP3 player. They are small headphones that sit on the cupped area around the ear canal. They generally do not provide the best sound quality but are highly efficient [56].

Unlike baseball gloves, reconfigurability has already been incorporated into several aspects of headphones. Many over ear and on ear headphones come with headbands that are adjustable to accommodate varying head shapes. Typically, to adjust the headband size, a individual must extend the ear piece out until they acquire the best fit. An example is shown in Figure 4.8(a). Another method is used in self adjusting headphones. An additional reconfigurable headphone aspect is the interchangeable ear pieces that come with the majority of in ear headphones. The ear pieces come in three sizes: small, medium, and large. These sizes allow the user to choose an ear piece size that best fits into their ear canal. A pair of Sony headphones with interchangeable ear pieces are pictured in Figure 4.8(b). Often the same headphones will come in many different colors or designs in order to appeal to different consumers. Some headphone manufacturers have incorporated this into the design of reconfigurable headphones. These reconfigurable headphones will come with interchangeable color caps, allowing the user to change the headphones to look the way they would like, as often as they would like. The ability to change a headphone's color has been incorporated into many different size headphones: over ear, on ear, in ear. Figure 4.8(c) shows a pair of in ear headphones with interchangeable color caps. Another reconfigurable headphone is the folding headphone, which is pictured in Figure 4.8(d). Some headphones are rather large and bulky, especially when compared to in ear headphones and ear buds. The ability to fold the headphones allows the consumer

(a) adjustable headband (b) interchangeable ear piece (c) interchangeable color caps (d) folding headphones (e) plug adapters

Figure 4.8: Product examples that currently incorporated reconfigurability into headphone design [46, 47, 48, 49].

to have these larger headphones without taking up as much space when in storage or transport. One last reconfigurable aspect to headphones are plug adapters; a few are pictured in Figure 4.8(e). The plug adapters allow the user the ability to use their desired headphones in many different environments. For example, airplanes require a different headphone plug than the standard. An airline plug adapter allows the user to use their own headphones while watching movies provided for viewing on the plane.

4.2.2 Reconfigurable Possibilities

Based on the headphone variations identified using the reconfigurability areas, some prospects for the implementation of reconfigurability were discovered. The prospects were chosen in a similar manner as presented with the baseball glove; all variations presented in Appendix B were considered as potential reconfigurable possibilities, the means of reconfiguration were to used to generate concepts, and two possibilities were chosen based on the identification of concepts. However, the headphones were to also be examined for the possible improvement of already existing reconfigurability. For this purpose, the reconfigurable headphones were studied specifically. The reconfigurable headphone possibilities identified are: an alternative to the current methods of headband adjustability, the combination of two headphone variations, and the combination of two different headphones types. Each possibility will be provided in more detail below.

(a) extending (b) self adjusting

Figure 4.9: Two methods by which headphone headbands currently adjust: extending and self-adjusting [46, 50].

Headband Adjustability

Much time and effort has been put into the lines, shapes, and forms of headphones. However, although it allows for the accommodation of a wide range of individuals, incorporating adjustability into the headband often has negative effects on the aesthetics of the headphones. Currently there are two general methods used when integrating adjustability into the headband: extending and self adjusting. An example of each is pictured in Figure 4.9. Having a headband be adjustable in the method shown in Figure 4.9(a) can take away from the headphone's aesthetics. When the headband is at its smallest size, there is a distinct smooth line between the headband and the earpiece. However, if the headband is extended to accommodate a larger size, the smoothness of this line is broken. On the other hand, the self-adjusting headphones appear more aesthetically pleasing on people with larger heads. For individuals with smaller heads, the headphones can stick out significantly above the top of the head.

Using the sample of reconfigurable products, it was noticed that another method of adjusting length is with the use of modularity, similar to that of the Accu-Length Expandable Junior Golf Clubs. The user would use inserts to adjust the length of the headband. The inserts would be of the same width and thickness as the rest of the headband, allowing for the continuation of the smooth line from the headband to the earpiece. One limitation with this design is the size of the inserts. The self-adjusting headphones use continuous adjustability to provide an optimal fit for a wide range of users. On the other hand, the extending headphones use small increments in their adjustability, providing good fits for a wide range of users. Therefore, the inserts in the modular design must be small enough to provide sizes to fit a significant portion of the population, but not too small, making users with larger heads spend significant time inserting the additional modules.

It may seem as though having to constantly remove or insert modules to obtain the correct headband length could become a tedious task. However, a pair of headphones is typically only used by one individual. Therefore, the headband would not require frequent adjustments. Instead, the proper number of inserts would only be required to be inserted once. Then, more inserts can be added or removed should another individual use the headphones.

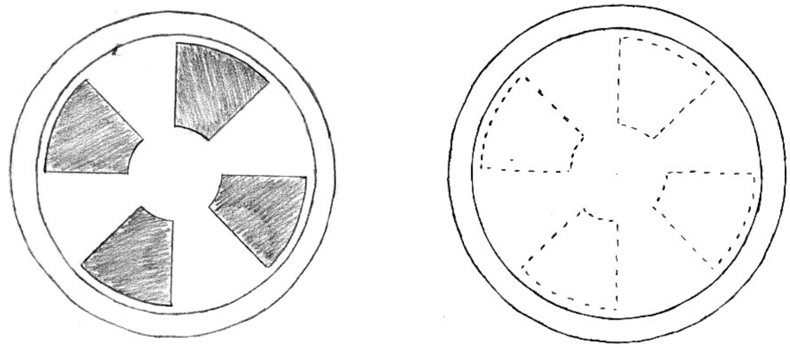
Open/Closed Back

One new possibility considered at was the combining of open back and closed back headphones. There are times when the user may want to hear what is going on around them and times when they may prefer to be isolated. For example, if an individual is riding their bike, they would like to be able to hear the cars and other people around them. However, if this same individual was on an airplane, they would most likely want to be isolated from the surrounding noise of the plane and other passengers. Currently, the only method of achieving both conditions is to purchase two sets of headphones.

Combining the two styles of backs would most likely not provide as complete an isolation as dedicated closed back headphones; the seals would create leaks. This is often the case when designing a reconfigurable product. There tends to be a slight loss of capability with at least one of the configurations. This loss is obviously not desired, but is a function of incorporating several different aspects into a single product.

To generate concepts, the four means of reconfiguration were used. Each mean was examined individually in order to generate distinctly different concepts. In Figures 4.10, 4.11, and 4.12, the shaded sections represent open areas and the dashed lines represent covered elements.

Modular: In order for a product to be modular, it must contain elements that can be

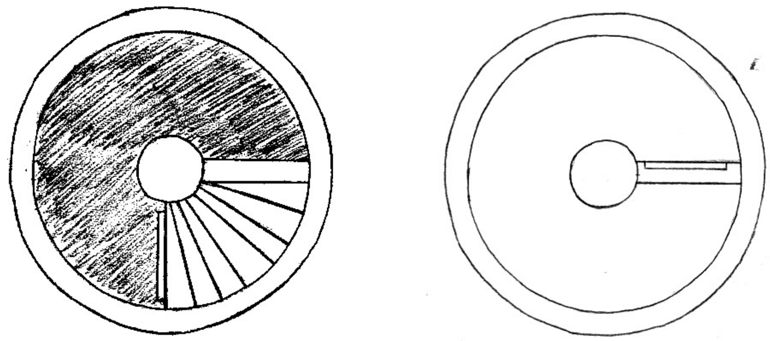


(a) open (b) closed

Figure 4.10: Concept drawings exhibiting the use of modular reconfiguration to obtain open and closed back headphones.

removed or substituted. This being the case, a method of adding or removing material to transfer from open to closed back and vice versa was generated. The concept created was the use of a cap to cover the holes in the open back headphones. The headphones will be open back with a lip around which the caps can lock onto, as pictured in Figure 4.10(a). When the cap is applied, all openings in the back are sealed, as pictured in Figure 4.10(b). An added benefit with this method is the possibility to create caps of different colors and designs, providing the user with many possibilities. However, a downside to the modular design is the fact that, when not in use, the caps must be carried around separately allowing for the possibility of them being lost.

Expand/Collapse: The expand/collapse concept was generated based on the design of folding doors. The concept uses an accordion-like design which can be compressed to only cover a portion of the ear piece back when open headphones are desired, as shown in Figure 4.11(a). On the other hand, when closed headphones are desired, the cover can be extended around the circle track to cover the entire back of the ear piece. A benefit of this design is the fact that all materials are incorporated directly into the design of the ear piece. The user is not required to carry around any added materials to reconfigure the product. Also, the user would be able to choose how open or closed they would like the headphones; they would be able to adjust the cover to almost any position they would like. However, in order for that cover material to be extended and compressed



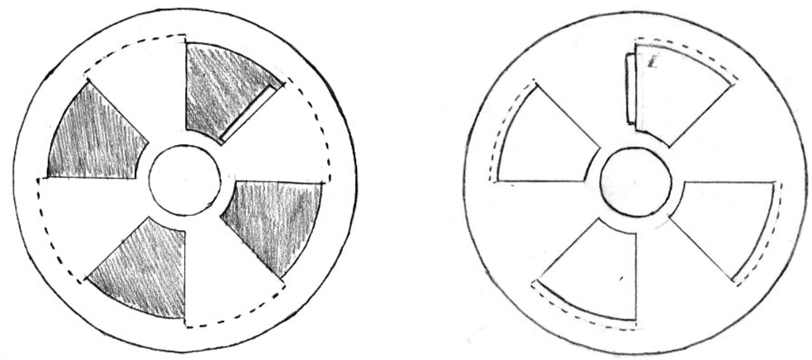
(a) open (b) closed

Figure 4.11: Concept drawings exhibiting the use of expansion and compression to obtain open and closed back headphones.

as intended, it will have to be rather thin and flexible. This being the case, when the headphones are in the closed configuration, they may not do a proper job of isolating the listener.

Concealment: The concealment concept was generated based on the fact that some aspect of the reconfiguration needed to be hidden out of sight. One possible method to achieve this would be to hide the materials under the part of the headphone back. The concept generated was to have the ear piece back divided into equal sections, with half of these sections open and half of them closed. There would also be a solid piece of plastic shaped to fit under all the closed sections; this is the hidden element, pictured in Figure 4.12(a). To close the headphones, the solid hidden piece would be rotated until the openings are covered, as pictured in Figure 4.12(b). Again, a benefit to this design is the fact that all materials are incorporated directly into the design of the product. One disadvantage, again, are the seals where sound could penetrate or escape.

The concept generated under concealment can also be considered reorientation, since the piece being concealed is being reorientated to cover and uncover the openings. That is the reason there is no separate concept for reorientation.



(a) open (b) closed

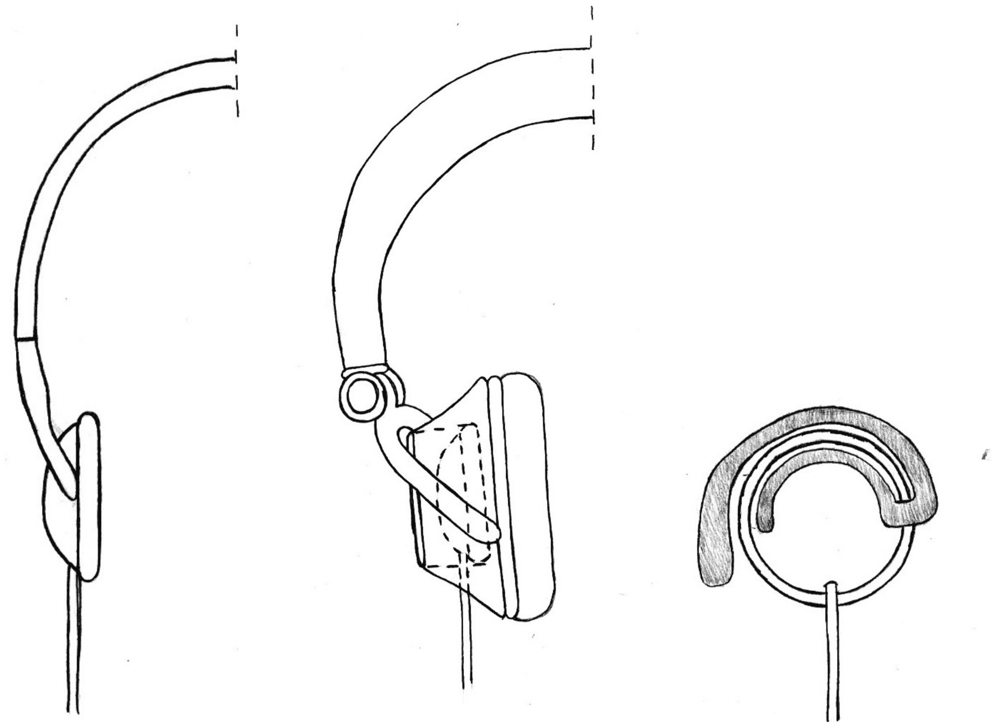
Figure 4.12: Concept drawings exhibiting the use of concealment to obtain open and closed back headphones.

On Ear/Over Ear Headphones

The idea to combine two different style headphones was based on the fact that market segments for the different style headphones will typically overlap. Consumers will often purchase two different style headphones and use each type depending on the situation. The four means of reconfiguration were studied to determine the most fitting combination of headphone styles and their possible solutions. The best and most feasible solution generated was the combination of on ear and over ear headphones.

The concept generated was the idea of detachable headphones. The user would be able to detach the speaker from the headband and attach a new headband depending on the type of style they wanted. Figure 4.13(a) shows the headphones in a typical on ear configuration. Then, Figure 4.13(b) shows the detached speaker inserted into the over ear headphones. To get the speaker into the over ear configuration, a cap on the back of the over ear earpiece would be removed, the speaker would be inserted into the opening in the earpiece, and the cap would be placed back on to cover the opening.

With the use of modularity to achieve the over ear and on ear headband configurations, the possibility for more potential options presented itself. As mentioned in the previous section, on ear headphones are available in over the head, behind the neck, and clip-on varieties. The detachable speaker with attachments provides the ability to achieve all three of these varieties. Figure 4.13(c) shows a clip-on configuration, where the shaded area is the attachment. The behind the neck version would use the same attachment



(a) on ear headband configuration (b) over ear configuration (c) on ear clip-on configuration

Figure 4.13: Concept drawings representing three possible configurations of the on ear/over ear reconfigurable headphones.

concept with a different style attachment.

4.3 Chapter Summary

In this chapter, the reconfigurability areas and the means of reconfiguration have been applied to two types of products: baseball gloves, where the market is controlled by dedicated products and the other, and headphones, where reconfigurability has already been incorporated into several of the market's products. The reconfigurability areas were used to identify variations between the many types of baseball gloves and headphones. With these variations, several prospects for the implementation of reconfigurabity were discovered. For each product, three prospects were chosen and the means of reconfiguration were used to generate possible methods for incorporating reconfigurability. For the baseball glove, all three prospects looked at new ideas, while for the headphones, one concept looked to improve upon an already existing reconfigurable element and the other two were new concepts.

CHAPTER V

DISCUSSION AND CONCLUSIONS

The objective of this thesis is to develop tools for designers to use in assessing the reconfigurability possibilities in products. To achieve this, a detailed study of reconfigurable products was performed. These products were studied with respect to many different aspects in hopes of identifying any distinguishing characteristics or patterns present. The main aspects studied were a product's reconfigurability area, means of reconfiguration, and number of configurations. The broader contributions of these three aspects in the new reconfigurable product development process and Designing for Human Variability are detailed in the following sections.

5.1 Reconfigurability Areas

Designers can use the reconfigurability areas to aid them in the process of designing a reconfigurable product. The reconfigurability areas can be used to identify possibilities for the incorporation of reconfigurability. This is achieved by distinguishing between variations of similar products, as presented with the baseball glove and headphones in sections 4.1.1 and 4.2.1 respectively. Also, reconfigurability Area 1, people use one product two different ways, allows the designer concentrate on other possible uses for the product. For example, with the baseball glove, users will often use their glove to carry items, such as a sports drink. The areas allow the designer to focus on one area at a time looking for specific variations or uses that fit, instead of focusing on the entire product as a whole. The reconfigurability areas may also provide areas that have not been considered to be studied. These factors have the potential to provide variations and uses that may not have been considered otherwise. Many of the variations and alternate uses identified will have the potential to become a reconfigurable product. The designer must narrow down the list based on their specific criteria.

5.2 Means of Reconfiguration

The four means of reconfiguration can aid the designer in concept generation. They provide designers with a basis to reference when generating concepts. Knowing that these means are methods by which a product can reconfigure allows the designers to focus on these means and provide distinctly different concepts, as with the concepts presented in the previous chapter.

Methods have already been identified to implement the three transformation principles in the concept generation phase of the new product design process for a transforming product [78, 77]. Skiles et al. [78] presents a method for the use of transformation principles in mind mapping. Singh et al. [77] presents a complete methodology for Design for Transformation with the use of transformation principles and facilitators in concept generation using transformation cards (“T-cards"), design by analogy, and mind mapping. Mind mapping with transformation principles has been utilized in a few other papers as well [62, 76].

The same methods can be used with the means of reconfiguration. In addition, the means of reconfiguration, with the addition of reorientation, provides a designer with even more possibilities for the design of reconfigurable systems. When a designer uses the current list of the three transformation principles, expose/cover, fuse/divide, and expand/collapse, their concept ideas are limited to concepts that only fit into these categories. The addition of reorientation expands the design field, providing the designer with the possibility for a broader range concepts. For example, if only the three original transformation principles had been used, the reorientation concept for the right/lefty baseball glove, presented in section 4.1.2, would probably not have been generated.

5.3 Number of Configurations

While studying the sample of reconfigurable products in terms of the number of reconfigurations, it was noticed the vast majority of products with only two configurations reconfigured via transposition. This pattern can be utilized by designers in the concept generation phase. If a reconfigurable product replacing two dedicated products is to be designed, the designer can first focus on the use of transposition for possible concepts. That is not to say that transposition should always be used for products with only two configurations. Instead, it should be used as a starting point for the generation of concepts. For example, the short stop/pitcher's glove concept presented in section 4.1.2 is a product with only two configurations, but it does not use transposition to reconfigure.

5.4 Designing for Human Variability

The tools presented with this research have the capability to be applied to Designing for Human Variability. DfHV is the design of products and environments that are robust to the variability in users. To accommodate this variability, designers typically will use sizes and/or adjustability. The incorporation of adjustability into a design is a method of incorporating reconfigurability. Section 3.5.1 presents a study of reconfigurable products that pertains specifically to the incorporation of adjustability to accommodate human variability. These reconfigurable products incorporated reconfigurability to accommodate variations in anthropometry, motor skills, attention span, strength, and skill level.

5.4.1 Reconfigurability Areas

When attempting to apply the reconfigurability areas to DfHV, designers are most likely to be successful when utilizing reconfigurability Areas 2 and 3. Reconfigurability Area 2 consists of similar products designed towards different market segments. Products are often separated in terms of market segments as a means of identifying the specific wants and needs of a certain group of people. Reconfigurable products located under Area 2 combine these similar products in different market segments as a way of attracting a larger market segment or extending a product's use cycle. Since variations in motor skills, attention span, strength, and skill level are typically regarded as different market segments, the development of reconfigurable products focused on these variations should concentrate on identifying product variations located under reconfigurability Area 2. Reconfigurability Area 3 consists of products that have multiple sizes to accommodate different portions of the population. These multiple sizes are designed as a method of accommodating people of varying anthropometric dimensions. Reconfigurable products located under Area 3 combine the multiple sizes of a product into one product, allowing for a wider range of accommodation with a single product. Therefore, if the focus of the reconfigurable products is accommodating variations in body dimensions, the designer should concentrate on identifying product variations located under reconfigurability Area 3.

5.4.2 Means of Reconfiguration

Section 3.5.1 also acknowledges that accommodating human variability can be achieved with the use of any of the four means of reconfiguration. Therefore, when designing with a focus on reconfigurability and DfHV, all means of reconfiguration can be used to generate reconfigurable concepts. However, certain means of reconfiguration should be considered more highly when incorporating reconfigurability to accommodate variations in certain areas, such as anthropometry, strength, and children. The information presented in this section are merely guidelines. It should not solely be used to determine the means of reconfiguration used by a product. All means of reconfiguration should be considered when designing a product and the design criteria should be the final factor in the selection of a product concept.

Anthropometry

When designing for a length change in anthropometry, such as stature, the use of *expansion/compression* should be considered. In the sample, 14 of the 15 products that were adjustable for varying anthropometries due to varying lengths used expansion/compressions as their means of reconfiguration. The next possible mean of reconfiguration to consider is *modularity*. With modularity, inserts can be added or removed to adjust the length of the product to accommodate different users. Modularity is not as highly considered as expansion/compression because expansion/compression incorporated all needed materials into the product design, while modularity does not. On the other hand, if the variation in anthropometry is not due to variations in length, but instead to variations in angle, such as the angle of the foot in reference to the lower leg, *reorientation* should be the first consideration. Reorientation allows a user to easily adjust the angle of some aspect of the product to match their needs. *Concealment* is the last means of reconfiguration to consider when designing for variations in anthropometry. The different configurations of a product utilizing concealment typically provide different functions. Since the products designed for variations in anthropometry provide configurations with the same function, concealment is not the ideal method of reconfiguration.

Strength

To accommodate variations in strength, weight must be added or removed or tension must be increased or decreased. The adjustment of weight is generally achieved with the use of *modularity*, such as in adjustable dumbbells. Modularity provides a quick, efficient way of adjusting weights. To increase or decrease tension, *expansion/compression* can be used. The more tension desired, the farther the extension and vice versa. The use of *concealment* and *reorientation* are not as prominent in reconfigurable products for varying strengths. Concealment generally provides a different function for each of the configurations, whereas products for varying strength provide the same function. On the other hand, reorientation typically does provide the same function, however, it only provides a new look of feel; to accommodate variations in strength something must be increased or decreased.

Children

As mentioned in Section 3.5.1, the use of reconfigurability to accommodate variations in children is a common tool used by designers. Children have rapid growth in both anthropometry and development. Reconfigurability helps to increase a product's use cycle. To accommodate the rapid anthropometric growth of a child the anthropometry suggestions presented above would be used. To accommodate developmental growth, such as attention span and fine and gross motor skill, other suggestions are required.

As a child gets older their attention span become longer. To accommodate the increased duration of attention span the product might become longer. To increase duration the fundamental process of reconfiguration *addition/subtraction* is typically used; addition/subtraction consists of *expansion/compression* and *modularity*. The best method of achieving this growth is with the use of modularity. Modules can be mixed and matched together to provide various durations of the same product, such as in Candy Land's Sweet Celebration board game. The duration increase may also be increased with the use of expansion/compression. *Reorientation* can be used should the process of reorientation provide an alternate longer path, similar to a railroad switch. Since *concealment* generally provides a different function for each of the configurations, it is not the best option when designing for attention spans.

Accommodation of the development of fine and gross motor skills can be easily be achieved using any means of reconfiguration. One is not more prominent than another in any way.

Although modularity is presented as the best means to accommodate the growth of attention spans, when possible, it may be best to avoid the use of modularity when designing for children. Children tend to be irresponsible with their possessions and modules could easily be misplaced.

5.5 General Guidelines

After performing research on the sample of reconfigurable products, all information was gathered together to generate general guidelines for designing reconfigurable products. The information was broken up in terms of reconfigurability area and means of reconfiguration.

5.5.1 Reconfigurability Areas

General guidelines for the reconfigurability areas are presented in this section. The guidelines represent distinguishing characteristics and trends identified within the areas during research. There are no guidelines present for reconfigurability areas 4 or 6 since there were no characteristics or trends identified under these areas.

Area 1: People use one products for two different purposes

- products typically use transposition
- no products contained infinite configurations
- products are neither evolvable nor survivable

Area 2: Similar products designed towards different market segments

- products with variability in motor skills, attention span, strength, and skill level are included under this area

Area 3: Same product, different sizes to accommodate different portions of the population

- products use addition/subtraction
- no products with only two configurations
- all products contain adjustability for human variability
- products containing both sizes for human variability and adjustability for human variability are located under this area
- products with variability in anthropometry are included under this area

Area 5: Similar products that perform different tasks

- all products are survivable

Area 7: Same product, different variations for consumer appeal

- all products utilize modularity
- no products with only two configurations
- no products contain infinite configurations

Area 8: Product is reconfigurable for storage purposes

- no products contain infinite configurations

5.5.2 Means of Reconfiguration

General guidelines for the means of reconfiguration are presented in this section. The guidelines represent distinguishing characteristics and trends identified with the means during research. Transposition and addition/subtraction are also included under this section as they are groupings of the means of reconfiguration.

Concealment

- typically used for a fixed set with few configurations

Modular

- typically used for a fixed set with many configurations
- products provide multi-ability, evolvability, and survivability
- only modular products provide evolvability
- all products under Area 7 are modular

Expansion/compression

- products can be designed to achieve either a fixed set of configurations or be unique every time
- typically used when accommodating length changes in anthropometry

Reorientation

- products can be designed to achieve either a fixed set of configurations or be unique every time
- typically used when accommodating non length related anthropometric changes

Transposition

- products with only two configurations typically use transposition
- large products generally use transposition
- products under Area 1 generally use transposition

Addition/subtraction

- products under Area 3 typically use addition/subtraction

5.6 Limitations and Future Work

As mentioned previously, the sample of reconfigurable products used for this paper is incomplete. It would be nearly impossible to construct a complete list, especially with an ever-changing marketplace. This sample was simply meant to provide a representation of the many different types of reconfigurable products. This sample of 90 products was, however, larger than samples used to make conclusions in several other papers, including [65], [66], and [75]. Nevertheless, there is the possibility of something being overlooked or not included. Reorientation provides an excellent example of this. Singh et al. were certain that their list of three transformation principles was all inclusive. However, this research has proved that to be false. The identification of reorientation leads to the question of whether all methods of reconfiguration used by products with multiple configurations have now been identified. It is possible that a few products incorporate a rare form of reconfigurability within their design that has yet to be studied. It is impossible to study every reconfigurable product to be certain. Nevertheless, new discoveries may aid in the design of these products.

Although reconfigurable products are available and have been available for some time, much work still needs to be done in order to better understand these products. While determining relationships between reconfigurable products, several questions arose. These questions pertain to much of the information covered in this paper and have not fully been answered by anyone in the area of reconfigurability.

- Are there certain factors that determine whether or not a product should be made reconfigurable?
- What are the distinguishing characteristics that make it so that some products in a given area are made reconfigurable while others in that same area are not?
- When should there be only one reconfigurable product and when should there be sizes?
- A reconfigurable product typically resembles one of the dedicated products it is replacing more than the others. Is there a method for which product is chosen to be closest resembled?
- If a product is made reconfigurable, is there a method for determining how much reconfigurability should be added?
- What effect does making a product reconfigurable have on the product itself?
- Are the means of reconfiguration approached differently within different areas, such as manufacturing, robotic, etc.? It may be that it is more common to use a certain means of reconfiguration depending on the area for which the product is being developed.

These are just a few of the intriguing questions in the area of reconfigurability. As research efforts continue, more questions are bound to arise.

APPENDICES

APPENDIX A

TABLE OF RECONFIGURABLE PRODUCTS

A table of all 90 reconfigurable products used to obtain the data presented in this paper is provided in this appendix. Below are some abbreviations that have been used in the creation of the table.

Table Header:

AHV-Adjustable for Human Variability, SHV-Sizes for Human Variability

Table Content:

Sizes: S-Small, M-Medium, L-Large

Multi-ability, Evolvability, Survivability: M-Multi-ability, E-Evolvability, S-Survivability

States: unk-unknown, inf-infinte

Transpose/Add/Subtract: T-Transpose, A-Add/Subtract

Area	Reconfigurable Product	Size	Multi-ability, Evolvability, Survivability	States	Adjustable	AHV	Sizes	SHV	Means of Reconfiguration	Transpose/ Add/Subtract
1	Futon	M	M	2			S		Reorient	T
1	Cane Sword	S	M	2			S	S	Conceal	T
1	Chameleon Blanket-Pillow	S	M	2			S		Conceal	T
1	Sleeper Sofa	M	M	2			S		Conceal	T
1	Counter Chair Step Stool	M	M	2					Conceal	T
1	DOC sofa/bunk bed	M	M	2					Conceal	T
1	Kewb Chair/Table	M	M	2					Conceal	T
2	Fisher Price Grow with Me Kitchen	M	M	2	A	A			Expand	T
2	Little Leaps Grow with Me Learning System	S	M	2	A	A			Conceal	T
2	Sleep Number Bed	M	M	101	A	A	S		Expand	A
2	4 in 1 crib	M	M	4	A	A			Expand	A
2	Candy Land Sweet Celebration	S	M E S	unk	A	A			Modular	A

Area	Reconfigurable Product	Size	Multi-ability, Evolvability, Survivability		States	Adjustable	AHV	Sizes	SHV	Means of Reconfiguration	Transpose/ Add/Subtract
2	Hospital Bed	M	M	S	inf	A	A			Reorient	T
2	Little Tikes 5 in 1 Adjustable Gym	M	M	S	5	A	A			Reorient	T
2	Boon Benders Adaptable Utensils	S	M		inf	A	A			Reorient	T
2	Expandable Backpack	S	M		2	A		S		Expand	A
2	Adjustable Bed Frame	S	M		3	A		S		Expand	A
2	Extendable Ice Scraper	S	M	S	inf	A		S		Expand	A
2	Recliner	M	M		2	A				Reorient	T
2	V-22 Osprey	L	M		2	A				Reorient	T
2	Multi Game Table	M	M	S	2					Conceal	T
2	Flight Bathroom	M	M	S	3					Conceal	T
2	Convertible Purse	S	M	S	3					Conceal	T
2	Multiple Ink Pens	S	M	S	4					Conceal	T
2	7 in 1 Magnetic Travel Game	S	M	S	7					Conceal	T

Area	Reconfigurable Product	Size	Multi-ability, Evolvability, Survivability			States	Adjustable	AHV	Sizes	SHV	Means of Reconfiguration	Transpose/ Add/Subtract
2	Convertible Sports Shoe	S	M	E	S	3			S	S	Modular	A
2	Croozer 525	S	M	E	S	4					Modular	A
2	Lutron GRAFIK Eye	S	M	E	S	unk					Modular	A
2	SHIFT Bike	M	M			inf					Reorient	T
2	Coach Penelope Op Art Wristlet/Purse	S	M			2					Reorient	T
3	Ski Bindings	S	M			unk	A	A	S	S	Expand	A
3	Kids Adjustable Skates	S	M			4	A	A	S	S	Expand	A
3	Crutches	S	M			45	A	A	S	S	Expand	A
3	Portable Basketball System	M	M			6	A	A			Expand	A
3	Adaptable Table	M	M			10	A	A			Expand	A
3	Adjustable Computer Chair	M	M		S	inf	A	A			Expand	A
3	Wilson Aviator Indoor Court Googles	S	M			25	A	A			Expand	A

Area	Reconfigurable Product	Size	Multi-ability, Evolvability, Survivability			States	Adjustable	AHV	Sizes	SHV	Means of Reconfiguration	Transpose/ Add/Subtract
3	Fisher Price Grow with Me Trike	S	M			6	A	A			Expand	A
3	Accu-Length Expandable Junior Golf Club	S	M	E	S	6	A	A	S	S	Modular	A
3	Snowboard Binding	S	M			180	A	A	S	S	Reorient	T
4	FlexibleLove	M	M			inf	A	A	S		Expand	A
4	DB Fletcher Capstan Table	M	M			2	A	A	S		Expand	A
4	Motocycle (sidecar)	M	M	E	S	2			S		Modular	A
4	USM Haller Table	M	M	E	S	510					Modular	A
4	Pontiac Vibe	L	M			8					Reorient	T
5	Child's Desk/Easel/Chalkboard	M	M		S	3	A				Conceal	T
5	Transition Car	L	M		S	2	A				Reorient	T
5	NASA Morphing Aircraft	L	M		S	inf	A				Reorient	T

Area	Reconfigurable Product	Size	Multi-ability, Evolvability, Survivability			States	Adjustable	AHV	Sizes	SHV	Means of Reconfiguration	Transpose/ Add/Subtract
5	Street Flyer Retractable Skate Shoes	S	M		S	2			S	S	Conceal	T
5	Cuisinart Pro Classic 7-Cup Food Processor	S	M	E	S	7			S		Modular	A
5	Reconfigurable Manufacturing Tools (RMT)	L	M	E	S	unk					Modular	A
5	Convertible Grill/Rotisserie Barbecue	S	M	E	S	2					Modular	A
5	4 in 1 Multihead Hammer	S	M	E	S	6					Modular	A
5	Self Reconfigurable Modular Robots	S	M	E	S	unk					Modular	A
5	Sony Reconfigurable Controller	S	M	E	S	unk					Modular	A

Area	Reconfigurable Product	Size	Multi-ability, Evolvability, Survivability	States	Adjustable	AHV	Sizes	SHV	Means of Reconfiguration	Transpose/ Add/Subtract
5	Kelty Convertible Stroller Backpack	S	M S	2					Reorient	T
6	Pants/Shorts	S	M S	2	A		S	S	Conceal	T
6	Monroe Adjustable Shock Absorbers	S	M	131	A				Expand	A
6	Taylor Made R9 Driver	S	M S	24	A		S	S	Reorient	T
6	Grumman F-14 Tomcat	L	M	inf	A				Reorient	T
6	Reconfigurable Race Car	L	M	inf	A				Reorient	T
6	DivnickGolfł All-in-One Golf Club	S	M	34	A				Reorient	T
6	Convertible Fingerless Glove/Mitten	S	M	2			S	S	Conceal	T
6	Shoes with Adjustable Heels	S	M	2			S	S	Conceal	T
6	Convertible Car	L	M	2					Conceal	T

Area	Reconfigurable Product	Size	Multi-ability, Evolvability, Survivability			States	Adjustable	AHV	Sizes	SHV	Means of Reconfiguration	Transpose/ Add/Subtract
6	Osprey Meridian Wheeled Convertible Pack	S	M		S	2					Conceal	T
6	Retractable Roof Stadium	L	M			2			S		Expand	A
6	Michelin Morphing Tires	S	M			4			S		Expand	A
6	Adidas Excell 1C Pro Low Baseball Cleats	S	M	E	S	3			S	S	Modular	A
6	Upright Vacuum	M	M	E	S	7					Modular	A
6	Muti-lens Eyewear	S	M	E	S	3					Modular	A
6	Apple Macbook Plug	S	M	E	S	6					Modular	A
6	Safeco Convertible Hand Truck	M	M			2					Reorient	T
6	Appliance Doors	M	M			2					Reorient	T
7	Interchangeable Watch Set	S	M	E	S	66	A	A			Modular	A
7	Toy Railroad Track	S	M	E	S	inf	A				Modular	A

Area	Reconfigurable Product	Size	Multi-ability, Evolvability, Survivability			States	Adjustable	AHV	Sizes	SHV	Means of Reconfiguration	Transpose/ Add/Subtract
7	SMART Car	M	M	E	S	12					Modular	A
7	Stackable Furniture	M	M	E	S	250					Modular	A
7	Nike Energy Cheer Shoes	S	M	E	S	10			S	S	Modular	A
8	Murphy Bed	M	M			2			S		Conceal	T
8	Chess/Backgammon Box	S	M			2			S		Conceal	T
8	Swiss Army Knife	S	M		S	6			S		Conceal	T
8	Bloomframe Window/Balcony	L	M		S	2					Conceal	T
8	Monolith Steel Table	M	M			2					Conceal	T
8	Kenchikukagu Mobile Furniture	M	M			2					Conceal	T
8	Folding Chairs	M	M			2					Expand	A
8	Collapsible Cup	S	M			2					Expand	A
8	Hand Fan	S	M			2					Expand	A
8	Ping Pong Door	M	M			2					Reorient	T

APPENDIX B

RECONFIGURABILITY AREAS FOR PRODUCT GENERATION

BASEBALL GLOVE

1. One product used for two different purposes

   carry drinks

2. Similar products designed towards different market segments

glove/mitt	righty/lefty	closed/open webbing
closed/open back	shallow/deep pocket	finger sleeve
baseball/softball	leather quality	

3. Same product, different sizes to accommodate different portions of the population

   adult/youth/women

4. Same product different sizes to accommodate different numbers of people

5. Similar products that perform different tasks

   glove/mitt

6. Same product, different variations to be used in different environments

   warm/cold
   rain can ruin a glove

7. Same product, different variations for consumer appeal

leather colors
web designs

8. Product is reconfigurable for storage purposes

HEADPHONES

1. One product used for two different purposes

2. Similar products designed towards different market segments

over ear/on ear/in ear/ear bud
DJs/runners

3. Same product, different sizes to accommodate different portions of the population

headband sizes
interchangeable in ear
ear cup size

4. Same product different sizes to accommodate different numbers of people

multiple headphone jack

5. Similar products that perform different tasks

6. Same product, different variations to be used in different environments

waterproof	open/closed ear cup
plug type	noise reduction/canceling

7. Same product, different variations for consumer appeal

color/design
speaker size

8. Product is reconfigurable for storage purposes

retractable cord
folding headphones
rotating ear cups

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