IDENTIFYING PRODUCT SCALING PRINCIPLES

A Thesis

by

ANGEL GERARDO PEREZ

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2011

Major Subject: Mechanical Engineering

IDENTIFYING PRODUCT SCALING PRINCIPLES

A Thesis

by

ANGEL GERARDO PEREZ

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Chair of Committee,	Julie Linsey
Committee Members,	Richard Malak
	Michael Johnson
Head of Department,	Dennis L. O'Neal

August 2011

Major Subject: Mechanical Engineering

ABSTRACT

Identifying Product Scaling Principles. (August 2011)

Angel Gerardo Perez, B.S., The University of Texas Pan American

Chair of Advisory Committee: Dr. Julie Linsey

There are countless products that perform the same function but are engineered to suit a different scale. Designers are often faced with the problem of taking a solution at one scale and mapping it to another. This frequently happens with design-by-analogy and bioinspired design. Despite various scaling laws for specific systems, there are no global principles for scaling systems, for example from a biological nano scale to macro scale. This is likely one of the reasons that bioinspired design is difficult. Very often scaling laws assume the same physical principles are being used, but this study of products indicates that a variety of changes occur as scale changes including changing the physical principles to meet a particular function. Empirical product research was used to determine a set of principles by observing and understanding numerous products and natural analogies to unearth new generalizations. The function a product performs is examined at various scales to view subtle and blatant differences. Principles are then determined. A case study validating the principles is also presented. Future work will validate and measure the effectiveness of the principles for design.

ACKNOWLEDGEMENTS

I would first like to thank my advisor, Dr. Linsey, for her guidance, encouragement and support. Throughout my thesis period, she directed me in the right direction, answered all the questions I asked and provided a lot of great ideas. Thanks to the members of my committee, Dr. Malak and Dr. Johnson for their added support.

I would like to thank all my lab mates for their support as well as entertainment. I would also like to thank Texas A&M University and the Department of Mechanical Engineering for allowing me the opportunity to further my knowledge with such a traditional and exceptional institution. Thanks to all my colleagues and the department faculty and staff for making my time a memorable and joyful experience.

Thanks to all my friends for providing some needed fun. I wish to thank my entire family and adopted families for all their support and encouragement throughout my time at Texas A&M University. I especially want to thank my loving girlfriend for always being there for me and forcing me to study and work. Finally, and most importantly, I wish to thank my parents. Thank you for the daily phone calls and all the support and love. I dedicate this thesis to them.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

Page

Page

LIST OF TABLES

Page

1. INTRODUCTION

Engineers and designers constantly make alterations to existing products for mapping solutions from one scale to another in order to fulfill changing customer needs, bioinspiration and design-by-analogy. These changes may include altering a product to be more compact or lightweight, more efficient, or larger in scale for increased production. When such a product is redesigned, one possible process to follow is Otto & Wood's redesign product development and reverse engineering process (Otto & Wood, 2001). This process incorporates three main steps: reverse engineering, develop a redesign and implement a redesign occur. Within this process, numerous idea generation methods are utilized in order to determine new novel designs. A popular concept generation method is design-by-analogy. Examples of design-by-analogy methods include TRIZ (Altshuller, 1999) and the WordTree Design-by-Analogy Method (Linsey, 2007). This reverse engineering process and idea generation methods are typically used for redesigning a product to suit the same product scale; however, taking a product from one scale to another can be difficult. Alone, the reverse engineering process and idea generation methods fall short in providing a systematic approach to scaling a product to the desired level. A set of principles can make this process more efficient as well as improve on the design of the original product. The principles provide a means of processing the information gathered in the reverse engineering step in order to derive ideas based on specific details encompassed by the example products.

This thesis follows the style of *Artificial Intelligence for Engineering Design, Analysis and Manufacturing.*

A key area where scaling is difficult and principles can assist is within biomimetic design. Recently, there has been an increase in interest in studying and observing nature for solving engineering problems (Institute, 2008). Due to its early stages in design methodology, very little has been developed for converting these natural systems and scaling them from the original scale to the desired level. One study by Vakili describes ways to find possible natural analogies and from these analogies, generate ideas (Vakili & Shu, 2001). They accomplish this by defining the functionality of the desired system and then uncover a natural system that accomplishes that same function. Another study by Bogatyrev merges a widely used idea generation method, TRIZ, into one that can derive ideas from natural systems (Bogatyrev & Bogatyreva, 2009). Currently, natural systems are mimicked exactly or converted into mechanical or electrical systems. An example of this is seen in Figure 1; mimicking a gecko's climbing ability through van der Waal forces or converting the idea into a mechanical system through the use of magnets or vacuums (Pugno, 2008). The challenge with this natural system is scaling up to a level where humans can take advantage of its abilities. The new principles developed by this work will aid the process of converting the natural system to the desired scale. They will act as a guide that leads designers to possible ideas and features that can be implemented into the final concept.

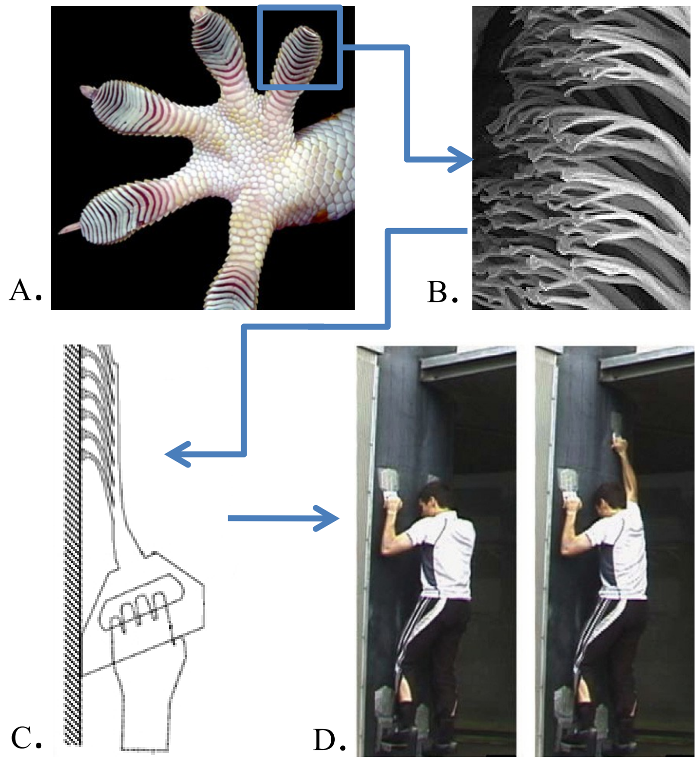


Figure 1: A. Gecko foot (Scientificamerican, 2010), B. Close up of gecko foot (Legacy.lclark, 2010), C. Solution one mimics the natural solution through van der Waals forces, D. Solution two converts and scales the system to a mechanical means through the use of magnets (Clingclimbing, 2010)

These scaling principles can benefit all areas of engineering and design, not just biomimicry. The objective of this thesis is to improve on the redesign process by identifying a set of design principles to assist engineers as they scale a system during design-by-analogy or bioinspired design. In this thesis, 46 example products and systems are gathered and studied, through an empirical research approach, in order to determine scaling characteristics throughout the product scales. The product scale consists of a small, medium and large product or system within each product class. The example product classes range from home appliances to farming equipment. This wide range of products aids in understanding many possible design changes throughout the product scales.

In understanding these product scale differences, six scaling principles and two energy checklists were derived. The scaling principles serve as a method to derive ideas for the desired scale based on the example products. They break the example products down to generate overall and specific design ideas. In order to take full advantage of these principles, a redesign and reverse engineering process similar to Otto and Woods' must be followed (Otto & Wood, 2001). This process is important because of the preliminary steps it requires which break down the example products by parts and functions which the scaling principle are based on. In conjunction with the principles, the energy checklists aid in determining various combinations of possible power sources that can be used in the final design. This is important due to the realization that the energy source required to power a product is based on its scale, customer needs and design constraints.

Another objective of this thesis is to test the principles and checklists as a viable idea generation method through a comparative case study. The case study incorporates a design problem which was previously solved in order to compare the final concepts to view how the principles have an effect on the final design. This will show that the principles add a new and improved insight into scaling that has not been previously observed.

2. PRIOR WORK

Scaling is critical in many fields of engineering and design. There is plenty of work previously performed on scaling theory, including dimensional analysis, similitude and scaling laws. Scaling can also be applied to areas such as biomimetics, product design including prototypes and product platforms, and even nanotechnology.

2.1 Dimensional Analysis and Similitude

Scaling is based on the theories of dimensional analysis and similarity. Dimensional analysis is ‘a method by which we deduce information about a phenomenon from the single premise that the phenomenon can be described by a dimensionally correct equation among variables (Langhaar, 1951). This can be restated as a way to comprehend physical data without dimensions. This method reduces the complexity of problems to a simpler form by removing and simplifying certain variables the desired quantity depends on. It allows for the dimensionless parameters to be acquired in order for these variables to be removed. The Buckingham pi theorem is one way to determine the amount of dimensionless numbers that will come out of the equation. This is the number of dimensional variables minus the number of dimensions. Dimensionally correct in the definition refers to the same dimensions on both sides of the equation, or dimensionally homogeneous. Dimensional analysis is useful in a number of applications; including a “check” of units in equations, conversion of units and determining relationships when between product scales. It provides a tool for engineers to understand and infer how a scaled system will behave when scaling occurs. The main advantage of this theory is the fact that a solution can be acquired quickly because a detailed analysis does not have to be performed. On the other hand, a complete solution is not obtained as a detailed analysis would provide (Bridgeman, 1922).

There are several steps to properly use dimensional analysis in order to gain insight into scaled systems. These steps minimize the possibility of missing a parameter in the equation. Ipsen depicts a step-by-step approach that begins by first identifying all variables the desired quantity depends on (Ipsen, 1960). The next step in the process is determining the dimensions of these quantities in terms of length, mass, time etc. The last step is removing dimensions from the variables one at a time in order to obtain a dimensionless result.

Similitude or similarity is a relevant theory to dimensional analysis. Geometry was the first area where similitude was used. It was noted that two shapes with different sizes can be similar due to incorporating the same angles. Other types of similarity include kinematic and dynamic similarity. Kinematic similarity refers to two objects or systems that experience similar motions such as velocity or acceleration. Dynamic similarity is when two objects or systems experience similar forces. Similitude is used in a number of fields such as fluids, thermodynamics and dynamics. It can be used for testing scaled models in product design. 'The objective of a similarity method is to experimentally predict the behavior of the target system through an indirect scaled testing, alleviating complex system construction and testing effort'(Otto & Wood, 2001).

2.1.1 Scaling Laws

Scaling laws are the actual mathematical equations and models derived through dimensional analysis and similitude to obtain the estimated results. Within engineering design, these laws can determine how a design will perform as well as optimize the final design. They were first recognized by Galileo as seen in his Two New Sciences book (Galilei, 1638). In his book, he states numerous physical differences in everyday objects that no one distinguished previously. One insight that eventually led to a scaling law was the recognition that 'the surface of a small solid is comparatively greater than that of a large one because the surface goes like the square of a linear dimension, but the volume goes like the cube' (Peterson, 2002). This is symbolized as the area S varies like L^2 and the volume V varies like L^3 (Wautelet, 2001)

$S \sim L^2$

$V \sim L^3$

These are two of the simplest scaling laws in mechanics. From these basic insights, Galileo also recognized how forces have a greater effect on smaller objects than larger ones. His understanding of these concepts led to the theory of scaling and its usefulness within engineering.

As previously stated, countless scaling laws have been established for specific systems. Wautelet demonstrates a variety of simple generic scaling laws for mechanics, fluids, electromagnetism, thermodynamics and optics (Wautelet, 2001). A specific example of scaling laws is seen in a study by Carpinteri who derives scaling laws for mechanics of materials, specifically on crack propagation Carpinteri et al. (2006). By utilizing the dimensional analysis approach, scaling laws were derived in order to understand and estimate how crack growth occurs in materials such as concrete. With these laws, engineers can test how size and material property changes affect crack growth. Another study shows how laws of similarity were determined for wind turbine rotors in order for ease of optimization when scaling to the desired level (Peterson, 1984). The study depicts how certain scaling laws for varying changes such as rotational speed, radius of the rotor and even the incidence of the blades has an effect on the overall performance. This allows for the optimal design to be obtained quickly. Scaling laws have also been derived for optical lens systems as studied by Lohman (Lohman, 1989). They help determine necessary changes in lens configuration and dimensions when scaled.

There are countless studies related to deriving and applying scaling laws for specific systems. They provide insight into what specific details need to be altered when scaling, such as the equations that relate to structural requirements needed to be considered for a larger system. General scaling principles can be used in conjunction with dimensional analysis for a more efficient means of designing a scaled product.

2.1.2 Scaled Models

Prototyping and testing of a product or system is an important step in the design process, which relates to the previously described theories. They are used for a multitude of intentions, including verifying analytical and numerical models, keeping development costs low, as well as finding the performance and feasibility of a design (Otto & Wood, 2001). An example of this is testing a scaled airplane prototype in a wind tunnel to test its aerodynamic performance before manufacturing the full scale model (Bushnell, 2005). By utilizing the proper scaling laws, this scaled down model provides useful information on how the wing design will perform for the full-scale model. The scaling laws help engineers determine how to build the model in order to take that data to the desired full scale system. Material properties and structures can also be tested through scaled down models; however in some cases it might not be suitable. When dynamic loads are applied to structures as referenced by Oshiro and Alves, inaccurate values will be determined due to improper scaling laws (Oshiro and Alves, 2009). When this occurs, the model is said to be distorted or have imperfect similarity. These material choices for the desired product scale must be accounted for individually through proper analysis. Scaled model testing in conjunction with scaling laws help reduce design time as well as provide information on what necessary changes are required when scaling.

2.2 Biomimetics

It is known that natural systems have evolved over millions of years to adapt and thrive in numerous environments. These adaptations have been studied and tested in order to mimic or convert for our advantage. A product example of this is Velcro, as seen in Figure 2. It was developed by George De Mestral who observed Galiumaparine (goosegrass) and its fruits ability to cling to animals who came in contact with it Jackson et al. (2009). The plant and fruit were studied in detail to first understand how this occurred. Through close observation, the fruit revealed hook like prongs which would grab onto animal hairs. This system was mimicked as an efficient way to temporarily bond items together.

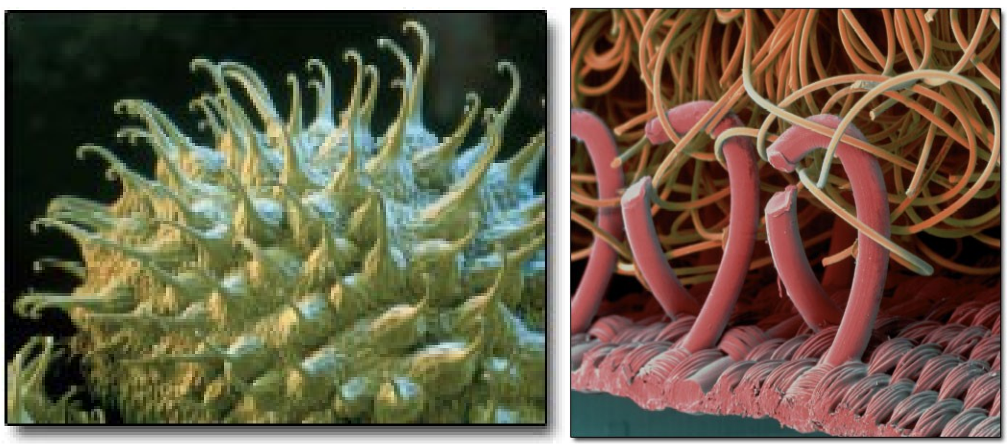


Figure 2: A. Goose grass plant (Openlearn.open A, 2011), B. Velcro close up (Openlearn.open B, 2011)

Another study by Pugno showed how they scaled gecko's feet and their ability to stick to various surfaces through the use of van der whaal forces (Pugno, 2008). They used this same principle and figured out a way to manufacture silicone pads that are scaled up versions of the gecko foot. In a study by Pack, this natural system is converted to a mechanical system by using a vacuum pump to stick to flat surfaces instead of van der whaal forces Pack et al. (1997). These two studies depict how through close observation and testing, a natural system can be scaled through mimicking or conversion.

Additional examples of converting natural systems include mimicking ground dwelling animals. Reptiles and insects have evolved dimpled skin or shells that does not allow for dirt and mud to stick to. This surface characteristic was introduced to multiple ground digging tools to accomplish this same task Ren et al. (2002). A similar system has been found with the lotus plant. Nosonovsky took this observation to produce a hydrophobic paint that can be applied to various surfaces to repel dirt, dust and water (Nosonovsky & Bhushan, 2005).

Relating to underwater systems, multiple studies have also proven the efficiency of fish swimming motion. One study by Lauder observes how a whale's fin allows for a lower drag coefficient due to the shape and placement of protruding nubs on the end of its fins (Fish & Lauder, 2005). They duplicate and scale the physical shape and features of the fin in order to produce wind turbine blades for producing electricity. A similar study takes the fins propulsion motion and converts it into a mechanical system for swimming robots and submarines Triantafyllou et al. (2005). In order for this to work, the motion was mimicked through the use of electric motors and mechanical systems. Scaling principles would add a systematic approach to converting these natural systems into a final product.

2.3 Product Platform and Product Families

Research in the area of product platforms and families is also associated to product scaling through their design methodologies. "Product family" is defined as a group of related products that share common features, components and subsystems and satisfy a variety of market niches Simpson et al. (2001). A product platform is the set of parameters (common parameters), features and/or components that remain constant from product to product, within a given product family. When product scaling occurs within companies, there is a possibility that a platform development was used to transfer components in order to increase efficiency. This is seen in a study by Simpson et al. (2006), who describes the sharing of automotive platforms in Volkswagen. They utilized the same platform for a number of different vehicle models that suited different market niches. Jiao et al. (2007) reviews product families and platform development in detail from its start. Areas such as product portfolio and platform-based product design are detailed.

A study by Sanderson illustrates the capabilities of a platform method used to keep the Sony Walkman on top of the market (Sanderson & Uzumeri, 1995). By maintaining a set of common components and platforms, the walkman was easily scaled to suit changing needs. Sony was able to scale the walkman down to half the original thickness by minimizing the scale of some parts and utilizing those parts for other models. Two of their most innovative parts, the ‘super flat motor’ and ‘chewing gum battery’, were typically used from one model to another. These two parts were small very small in scale at that time which enabled for smaller models to be developed. Topological changes to these and other components also allowed for a wide variety of designs. Other companies that utilized platform families and development include Black and Decker (Meyer et al., 1992), Xerox (Paula, 1997) and Canon (Yamanouchi, 1989).

There are also numerous studies that present methods to incorporate platform architecture into companies. This conversion will allow the companies to save money on development and increase the amount of models available, fulfilling numerous market niches and scales. Martin describes incorporating the design for variety (DFV) method to develop product architecture for a company's product line (Martin & Ishi, 2002). It integrates using generational variety index (GVI) and coupling index (CI) to measure the product line architecture in order to determine the best fit. Another study by Zacharias proposes a method which considers engineering and marketing combined to adapt platform architecture (Zacharias & Yassine, 2008). This model determines the cost as well as the amount of variants possible in a product platform conversion.

2.4 Nanotechnology

Miniaturization is another example of scaling to a micro and nano-level. The history of miniaturization is explained in a paper by Hsu (Hsu, 2002) who detailed the advances in technology throughout the years and how it has aided this new field. Within this area, automation and micromachining are important processes which led to products reaching smaller levels which fulfill new and continually changing customer needs. An example of this is within the medical field where small and precise tools are now required for fragile and delicate operations, such as a micro-drill Cheong et al. (1999). These advances have led to building devices in the atomic level called nanotechnology.

Another study describes how they are using nano-colloidal drug delivery systems for the delivery of genes and antigens to specific areas of the body (Denkba & Vaseashta, 2008). Carbon nanotubes are also being utilized within the automotive industry as a power source in fuel cells Korchagin et al. (2009). Due to their properties, they are being used as electro-catalysts for ethanol oxidation. Nanotechnology is the newest and most beneficial technology that is being utilized that incorporates scaling laws at the smallest scale. These miniaturization strategies can also be aided with general scaling principles as an overview.

The studies and information gathered proved valuable in understanding the vastness of scaling within the engineering community as well as what has been previously done. This includes the numerous physical principles, specific scaling laws, dimensional analysis and prototyping which can all be aided by these scaling principles. Based on this background research, the objective of this study is to define the principles to aid the process of scaling products and systems to the desired level. They will act as protocols to follow when heading in the desired scaling direction. The following sections present the method and results of this study.

3. EMPIRICAL PRODUCT STUDY

The scaling principles were derived through an empirical research process which incorporates searching, investigating and understanding example products and systems in order to reveal product scale differences. These differences provide guidance for the changes necessary when scaling a product, ultimately leading to the scaling principles and two energy check lists.

3.1 Method

Through an empirical product study approach, various products and systems were analyzed in order to derive the scaling principles. This technique is depicted in Figure 3 with a general process on the left and a detailed process on the right. Altshuller's 'The Innovation Algorithm: TRIZ, Systematic Innovation and Technical Creativity' (Altshuller, 1999), Singhs's et al. (2009) 'Innovations in Design Through Transformation' and Saunder's et al. (2009) 'The Characteristics of Innovative, Mechanical Products' all utilize this empirical research approach. Singh utilizes this method in the determination of transformation principles by studying transforming products while Saunders determines what makes a product innovative and successful in the market by studying and observing award winning products. This method allows for a thorough investigation into each example product for a better understanding on their differences throughout each product scale.

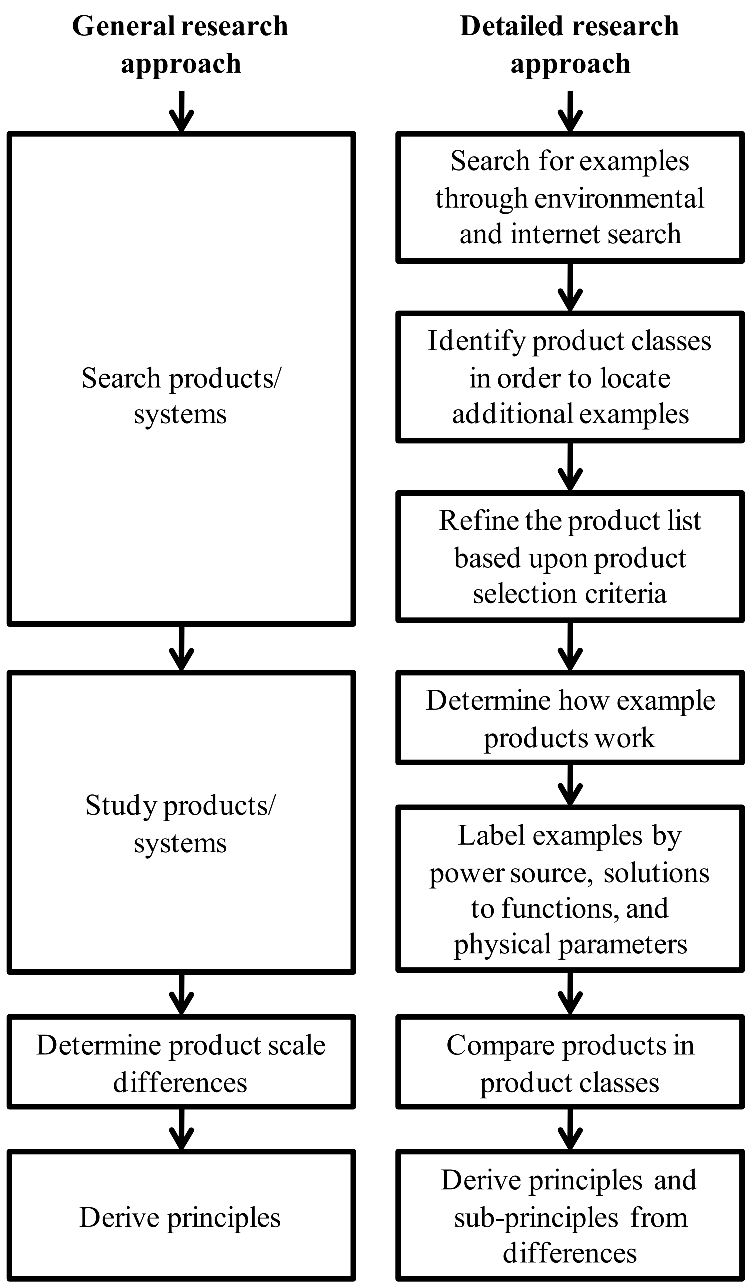


Figure 3: General and detailed empirical research approach Singh et al. (2009)

3.1.1 Product Identification and Search Method

Example products are necessary in the derivation of these scaling principles. The search method for the products is shown in Figure 4. First, preliminary products were selected by observing everyday environmental items. This involved searching for products around the house, office and even the city, in order to determine a preliminary list of items. Other means of determining preliminary products came from searching an online product database, Ebay, an online merchandise auctioning website. It uses a product category list to assist its users in finding their desired items. Searching through this list for new products, additional items were identified. These items were categorized based on general function, such as a nut cracker or coffee grinder, which allowed for a broader spectrum of items to be determined. In some cases, product categories were determined, such as agricultural equipment, which led to additional products such as a combine harvester and grain harvester.

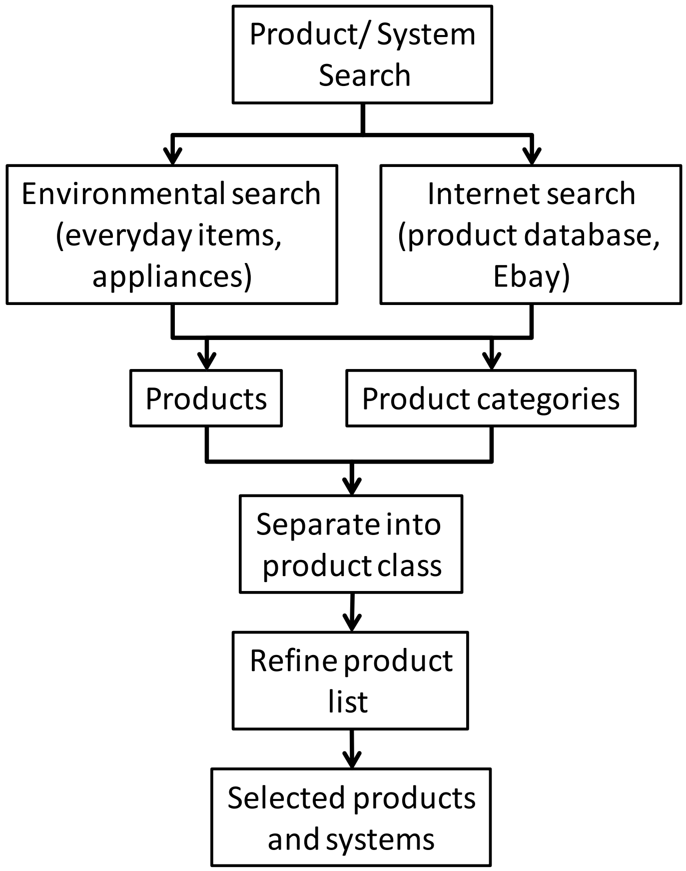


Figure 4: Product search method

Next, the preliminary products were grouped together based on their main function or product class. An example of this is a water filter, whose function is to remove harmful bacteria from water. From these product classes, additional products and systems were again identified by observing environmental items and searching the internet. Through the main function, filter water, an ultraviolet light purifier and a city water treatment plant were also identified. The final list of product classes, products and system examples were refined based on a number of criteria.

Table 1 shows the selection criteria for the classes, example products and systems. First, the product class must be extensive in order to contain a wide variety of products in various scales, which allows for numerous product changes to be observed (e.g., nano, micro, meso, macro). When refining the products/ systems, the example products and systems must be mechanically and/or electrically related due to author's background. Next, each product and system should be an end product; it should not be a mechanism or part of a product. Again, due to the class main function, the product and systems must perform this same function by any method. Finally, information on how the product and system work must be obtainable to fully understand each product in detail. This allows for a thorough examination into how the functions are performed and how they differ from one product to another.

Table 1: Product class, example product and system selection criteria Saunders et al. (2009)

- The product class must be extensive to aid in product variety
- The product and/or system must be mechanically and/or electrically related
- The product and/or system must be a market product, not just an individual part or mechanism
- The product and/or system must perform the same overall function as the product class
- Information must be available on how the product and/or system works or otherwise be obtained

Once all products were refined based on the product selection criteria, 46 products and systems were obtained. There were 17 total product classes, 12 contained three example products and 5 classes contained 2 products. This list incorporates a wide variety of product classes ranging from transporting dirt to making bread. It is extensive to provide insights into the product differences in order to derive the general scaling principles.

3.1.2 Investigating Products

Example products are labeled based on their "energy source", "solutions to functions", and "physical properties" to thoroughly understand how they work. The majority of this research was again web based relying on websites such as How Stuff Works, Google Search, Google Scholar and Texas A&M's online article library. This online article search utilizes other article databases to find related studies to the search entry. These databases include Academic Search Complete, Applied Science and Technology Full Text, and Science Direct. A number of books were also utilized such as *How Stuff Works* (Brain, 2001) and *The New Way Things Work* Macaulay et al. (1998).

"Energy source" in this study is defined as what powers a product or system. Through observation, systems were divided into two categories, user and machine activity. An example of a user activity is removing a pecan from the shell while a machine activity is an electric nutcracker cracking the shell.

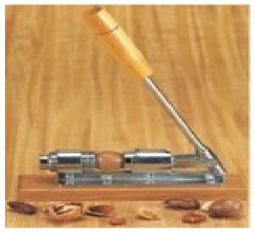
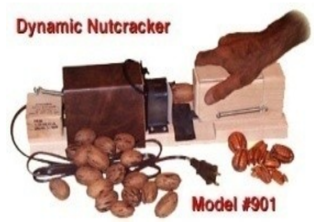
"Solutions to functions" relate to the products' overall function and sub-functions and how they are performed. The overall function is defined as the main function being performed, such as shelling for a shelling machine. Whereas the sub-functions are the individual functions or steps necessary to fulfill the overall function, such as import nut, form shell, export nut and separate nut from shell.

Products can also be separated into two categories, concurrent or non-concurrent systems. A concurrent system is defined as a system which can perform multiple functions at the same time; whereas a non-concurrent system is one that can only perform one individual function at a time (Dictionary.com, 2011).

"Physical property" is defined as "any property used to characterize matter and energy and their interactions" (Dictionary.com, 2001). This can be categorized into intensive and extensive properties. Intensive properties are scale independent, such as hardness, ductility, and elasticity. Extensive properties are scale dependent, such as stiffness, volume, and mass. Extensive properties are altered when scaling is required and intensive properties are not (Chemistry-Dictionary.com, 2011).

The three product characteristics, "energy source", "solutions to functions" and "physical properties", were summarized into an outline for ease of comparison between each product scale. The outline consisted of the main function performed, followed by each sub-function, under which power source, solutions to functions, and physical property for each product were under. The shelling machine outline is shown in Table 2 as an example with images of each mechanism. This method enabled the differences of each product to be easily compared.

Table 2: "Pecan Sheller" Product class examples with individual sub-functions, in functional basis, and how they are performed in order to easily review and compare each product class

Sub-functions	 Mechanical nutcracker (Faqs, 2010)	 Electric nutcracker (Lemfgco, 2010)	 Production nut sheller (Biodiesel-machine, 2010)
Import Nut	User Activity Place 1 nut into machine	User Activity Place 1 nut into machine	Machine Activity Conveyor belts
Form Shell	User Activity Hand operated lever	Machine Activity Electric powered mechanism	Machine Activity Electric powered blast of air
Export Nut	User Activity Remove nut from machine	User Activity Remove nut from machine	Machine Activity Electric powered bagger
Separate Nut from Shell	User Activity Hand pick nut from shell	User Activity Hand pick nut from shell	Machine Activity Electric powered blast of air

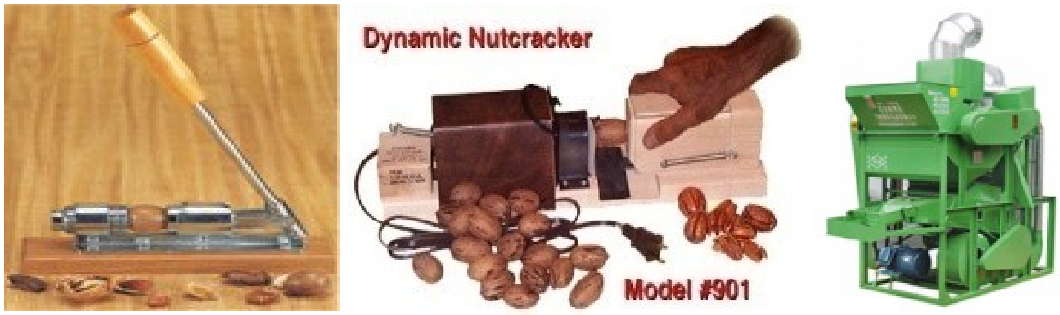
3.2 Results and Discussion

Continuing with the empirical research process, the example products in each class were compared to each other to reveal the scale difference and the scaling principles.

The following sections detail the example products, scaling principles in conjunction with the energy source checklists and the redesign process where the scaling principles are introduced.

3.2.1 Example Products

As previously stated, 46 products were gathered and observed in order to derive the scaling principles. The first example product category is “shelling nuts”. The nut shelling process varies drastically depending on the type of nut. For this example, the pecan and its shelling process is observed through three scales. In the smallest scale, a mechanical nut cracker is used to crack the shell in order to manually remove the nut from within, Figure 5A. A rotating handle transfers energy horizontally through a translating slide in order to crack the shell. With the invention of electricity and the electric motor, this product was adapted with this power source. The same method is utilized from the manual nut cracker to crack the nut with a rotating arm converted to a sliding motion. This addition of an electric motor causes the product to be slightly larger to accommodate for extra mechanical parts, such as the electric motor and arm that attaches to the existing mechanism. A production nut sheller was the largest machine analyzed, Figure 5C. This high production system also utilizes electricity for power. This machine differs from the last by using a concurrent system and a blast of air within a cylinder to crack and separate the nut from the shell. This machine also combines shelling and separating, which again makes the product more complicated and larger in scale, but easier for the user.



A. B. C.

Figure 5: Examples of pecan shelling machines A. Manual nut cracker (Faqs, 2010), B. Electric nut cracker (Lemfgco, 2010), C. Production shelling machine (Biodiesel-machine, 2010)

Table 3 depicts the full list of example products and systems utilized to determine the scaling principles.

Table 3: Comparison products

- **Saw**
  a) Hand saw
  b) Electric circular saw
  c) Gasoline powered chainsaw
- **Trencher**
  a) Pull plow
  b) Gasoline push trencher
  c) Gasoline ride trencher
- **Length Measurer**
  a) 12 inch ruler
  b) Tape measure

Table 3: Continued

- c) Laser tape
- **Building**
  - a) Wooden building
  - b) Concrete building
  - c) Metal and glass skyscraper
- **Dirt Transport**
  - a) Push wheelbarrow
  - b) Dump truck
  - c) Earth mover
- **Cut metal**
  - a) Hand shears
  - b) Bandsaw
  - c) Plasma cutter
- **Excavate Earth**
  - a) Shovel
  - b) Backhoe Excavator
  - c) Dragline excavator
- **Water Filtration**
  - **a)** Water bag filter
  - **b)** Uv light purifier
  - **c)** City water treatment plant
- **Tell Time**
  - a) Mechanical wrist watch
  - b) Electric wrist watch
- **Weight Scale**
  - a) Balance
  - b) Mechanical weight scale
  - c) Load cell truck scale

Table 3: Continued

- **Grain Harvesting**
  a) Scythe
  b) Grain harvester
- **Bread Making**
  a) Hand kneading
  b) Production bread making
  c) Electric home bread maker
- **Cotton Picking**
  a) Hand picking cotton
  b) Cotton picker
- **Press**
  a) Mechanical vice
  b) Hydraulic press
  c) 100 ton press
- **Air pump**
  a) Hand operated air pump
  b) Air compressor
- **Secure items**
  a) Combination lock
  b) Safe

3.2.2 Determining Product Scale Differences

Repeated patterns were recognized throughout the product scales, which led to the derivation of the scaling principles. The first four principles were realized from the "solutions to functions" portion of the product summary. This section was important in uncovering uncommon differences. When observing changes in product classes as the scale is decreased, steps or complete mechanisms are removed in order to simplify the system: this simplified process fulfills the “should”, not “musts”. An example of this is seen in Figure 6, where an air compressor system is simplified into a single hand operated air pump. The engine or power source from the air compressor is completely removed, converting a machine activity into a user activity.

A. B.

Figure 6: A. Hand air pump (Reviewsalert, 2011), B. Air compressor (Aircompressorhut, 2011)

The “solutions to functions” section also uncovered the fact that a products’ main function can be performed through a number of different methods. It was observed these completely different methods could increase or decrease the scale of the product or system. This can be seen in Figure 7 where a laser tape is similar in scale to a tape measure even though they measure distance with two completely different methods.

A. B.

Figure 7: A. Tape measure (Amazon, 2010), B. Laser tape (Williamcameronwoodworking, 2010)

Through this product class observation, it was also realized that certain parts and features remained unchanged even though the scale was different. Parts and components were shared among several product classes to fulfill sub-functions that were unchanged or slightly altered.

The fourth principle was determined by product differences as the product scale increased and decreased. In this case, the majority of the examples show how multiple manual steps are combined into one automatic system. Functions and sub-functions were also combined when scaling was decreased.

The “energy source” category of the product summary revealed the next scaling principle, which was expected. In the majority of the product groups, both user and machine activity systems were employed, where user activities were typically found in smaller scales and machine activities in larger scales. In some cases, a product might be scaled and designed for users without electricity or gasoline. In this case, natural resources available to the user must be utilized as an energy source, such as a nearby river.

The last principle relates to the physical differences in each product class, which was again expected. The size and material of the product, depending on the necessary capacity, is altered to suit each need. Topological changes were also noticed with the various placements of certain parts. With this realization, parameter change was the last principle created. These principles could not have been generated without these example products. Their span throughout the product scale helped in realizing the sub-principles as well.

3.2.3 Scaling Principles

Through our empirical product research method, six scaling principles were derived: ‘change energy source’, ‘simplify system’, ‘change method’, ‘combine functions’, ‘directly transfer components’ and ‘change parameters’. A description of each principle and energy source checklist supporting the ‘change energy source’ principle is described in detail in the following sections.

Change energy source- *Change energy source to a more efficient means or to better fulfill the desired customer needs and design constraints. Change a user activity into a machine activity. Use available natural resources when applicable.*

There are many energy sources available to power products and machines. First, human energy by the user can be utilized. This is typically found with smaller and lower cost products. When rivers or similar natural resources are available, they can be taken advantage of by users who do not have the luxuries of electricity or gasoline. An example of this is using a water mill to grind corn. When other energy sources such as electricity and fossil fuels are accessible, they allow products to be automatically run, increasing production and efficiency. These energy sources are typically used to power larger scaled products and machines. However, there are certain factors that need to be considered before choosing an energy source. These factors are related to the customer needs and design constraints required for the product, which is what determines the best energy source to utilize. Figure 8 depicts an example of a manual pecan cracker that is intended for home use and a production sheller powered by electricity for greater efficiency in production. The production sheller needs an energy source with a higher power density for the increase in production.

A. B.

Figure 8: Examples "change energy source" A. Mechanical nutcracker powered by the user (Faqs, 2010), B. Conversion to an electric production shelling machine (Biodiesel-machine, 2010)

Simplify system-*Remove and/or minimize user activities, steps in process and parts within product while still fulfilling customer needs. Find a way to perform the function in minimal steps, fulfill musts not shoulds. Look at customer needs and wants, activity diagram, product functions, sub-functions and product parts.*

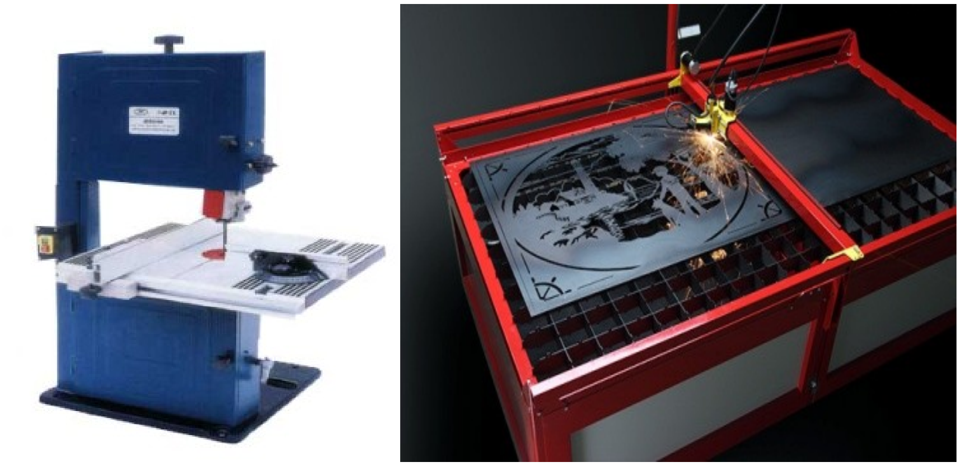
This principle can be used to take an existing product or system and minimize it in scale. In order to do this, one must fully understand the example product through various methods. This incorporates learning how the product works by taking the product apart to determine what components can be removed, replaced or simplified (Otto & Wood, 2001). It also includes understanding the customer wants and needs, user and machine activities and product sub-functions. If the product performs multiple steps to fulfill the function, the customer needs and wants must be analyzed. Many products try to appeal to the public's wants, when all that is required is fulfilling the need. Due to this, user activity steps and parts can be removed and the final product simplified. This simplification however might not satisfy the same sized scale. An example of this is shown in Figure 9, where a multi-step city water treatment plant that supplies water for thousands is simplified to a one step process for a couple of users. The water filter bag performs the main function of removing harmful bacteria; however the customer wants, such as clarity, is not met.

A. B.

Figure 9: Examples "simplify system" A. Multi-step city water treatment plant (Durhamcountync, 2010), B. Simplified to a one step portable filter bag by removing additional, unnecessary steps (Rei, 2010)

Change method- *Find an alternate method to perform the same function/sub-function to better fulfill customer needs. Change a user activity into a machine activity. Change the process that performs the function (e.g., physical to chemical). Design a new way to perform the current function, new technology. Adapt an existing product system/ mechanism to fulfill the current function. Look at customer needs and wants, activity diagram, product functions and sub-functions and product parts.*

This principle incorporates determining other possible solutions and ideas to the overall design problem as well as individual product functions and user activities. One way this can be accomplished is by using an existing product mechanism directly or through modification to perform the current function. An example of this is modifying a rotating potato peeler to string a guitar. Another way is to determine whether the function can be performed by changing the general process (e.g., a physical process converted to chemical). A completely new method can also be engineered to perform the desired function. An example of this is seen in Figure 10, where the physical sawing method in a bandsaw is converted to a plasma cutter to cut through metal. Due to this change in method, the user activities have also changed from physically holding the part being cut to telling a computer where to cut. These new solutions can increase or decrease the scale of the product depending on its complexity.



A. B.

Figure 10: Examples "change method" A. Bandsaw blade (Bandsawcutting, 2010), B. Replaced by a plasma cutter that converts gas into plasma to cut metal (Samsoncnc, 2010)

Combine functions-*Combine as many functions/sub-functions into one product as possible. Combine user activities. Make a single part perform 2 or more functions. Combine multiple mechanisms to be run from minimal number of power sources Combine separate individual parts together. Convert to a concurrent system, continuous process.*

This principle combines multiple steps or functions into one system which can ultimately make the final product larger or smaller in scale. Combining functions to be operated from one unit requires utilizing parts to perform several functions and multiple parts to be run from minimal power sources. This involves incorporating transmissions, drive shafts and even sprockets and chains to distribute the power among the various mechanisms. This allows for several moving systems to be powered from one motor, removing additional motors and saving space. Combining user activities also serves as a way to minimize the amount of user activities. If two functions can be combined, the product will require less input from the user, saving time. An example of “combine functions” is seen in Figure 11, where the bread making process requires the user to perform multiple activities and utilize multiple appliances, such as a mixer and oven. This process is combined into a single home bread maker that uses one rotating paddle to mix as well as knead the ingredients in one unit. This unit also contains a heating element in order to bake the bread where it was mixed. User activities such as hand mixing and kneading also decrease after converting the process to a machine activity. This smaller product fulfills the same function, however at a different production scale.

Combining functions can be aided by the addition of a concurrent process. This can be utilized in order for all functions to be performed at the same time. Conveyor systems can be implemented to help this process along by allowing a seamless transfer from one function to the next, making the process continuous.

A. B.

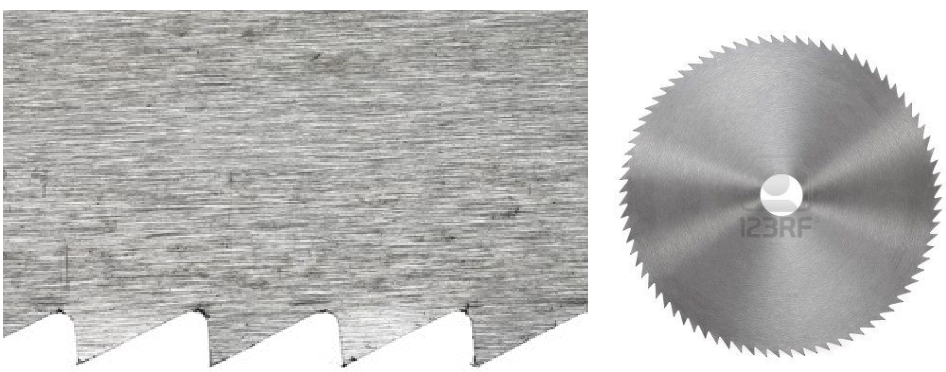
Figure 11: Examples "combine functions" A. Multiple tool bread making facility (Adventuresincapitalism, 2010), B. Combined into a single home bread maker (Homeinteriorshome, 2010)

Directly transfer components or features-*Directly transfer parts and/or features from original scale to the desired scale if applicable. If parts can still fulfill customer needs and design constraints, reuse in new design. Adapt existing part or feature to fit desired design.*

This principle relates to product classes and architectures where components and features are transferred from one product to another. When product scaling is performed, there is a chance that certain parts can be reused. If the part can still fulfill its function as well as the customer need and design constraints, transferring is preferable. The advantages to transferring parts includes minimizing the number of parts to manufacture, design and implement which in turn increases efficiency and saves the company money.

It also allows the company to produce a wider amount of products to appeal to different customers Simpson et al. (2001). This principle can be applied to both scaling up or down; however the scale change is typically small. Greater changes of scale would incorporate many more drastic changes to parts and features. Transferring would not be suitable in these cases.

An example of this principle can be seen in Figure 12, where the cross-cut teeth feature on a hand saw is transferred to a circular saw blade used in circular saws. This pattern is directly copied, which eliminates the need for the design team to test the pattern's wood cutting efficiency.



A. B.

Figure 12: Examples "directly transfer components" A. The teeth on a cross-cut hand saw (Homeconstructionshop, 2010), B. Transferred to a circular saw blade (123rf, 2010)

Change parameters - *Change material and/or physical parameters of individual parts to fulfill new customer needs. Change extensive properties (scale variant) to sustain new capacity loads. Change the physical location of individual parts to better fulfill customer needs.*

This principle observes the material properties as well as the physical scale of the overall product and its parts and the changes that are necessary to accommodate the desired capacity loads. Material selection is an important factor when designing a new product. Depending on the product's function and customer needs, the material choices can vary tremendously. From a lightweight portable hand drill made of metal and plastic to an all steel dump truck, the materials must meet the desired requirements. The capacity load determines the physical scale of the product. An example is shown in Figure 13, where a wheelbarrow used to transport approximately 1 cubic yard of material compared to an earth mover used to transport up to 400 tons of material. Observing only the bucket, the overall size differences can be seen. The volume of the overall bucket is increased to accommodate more material, which in turn increases the wall thickness of the bucket to sustain the load carried within. Other individual parts of the earth mover are also changed to accommodate the increased load, such as the wheels, tires, suspension and frame. Parameter change also includes changing the location of individual parts. This is typically performed to best meet the customer needs and improve product performance.

A. B.

Figure 13: Examples "change parameters" A. Wheel barrow's physical parameters (Blogs.riverfronttimes, 2010), B. Increased for an earth mover's new capacity needs (Budologyproductions, 2010)

3.2.4 Integrating the Scaling Principles into a Reverse Engineering and Redesign Method

The scaling principles are most effective as a part of a reverse engineering and redesign method. Due to the principles' focus on the example products, certain steps are required before the principles can be applied. A redesign product development process is implemented as the proper procedure to follow. These steps along with some additional tasks are necessary in order to take full advantage of its idea generation capabilities.

Otto and Wood's redesign product development process was chosen due to the clearly defined steps required to take a concept into the marketplace, Figure 14 (Otto & Wood, 2001). There are three main steps in this process, beginning with 'reverse engineering'.

This step includes selecting a product, develop a vision, customer needs analysis and market opportunity analysis. Within this step, the example products and desired scale direction is chosen. The example products are analyzed to understand how they work, including individual parts and mechanisms. This can help reduce the number of parts incorporated into the final product if size and weight is an important consideration. This reduction in parts is obtained by applying the ‘simplify system’ principle, focusing on its sub-function ‘remove and/or minimize parts’. Within the customer need analysis, customer needs in conjunction with customer reviews of the example products are determined. Customer reviews and analysis can include interviews, surveys and even internet reviews posted by customers who have physically used the product. These are helpful in determining customer likes and dislikes of certain features, parts and overall design of the example product. Market opportunity analysis involves studying the marketplace to determine if such a product is needed and its expected performance.

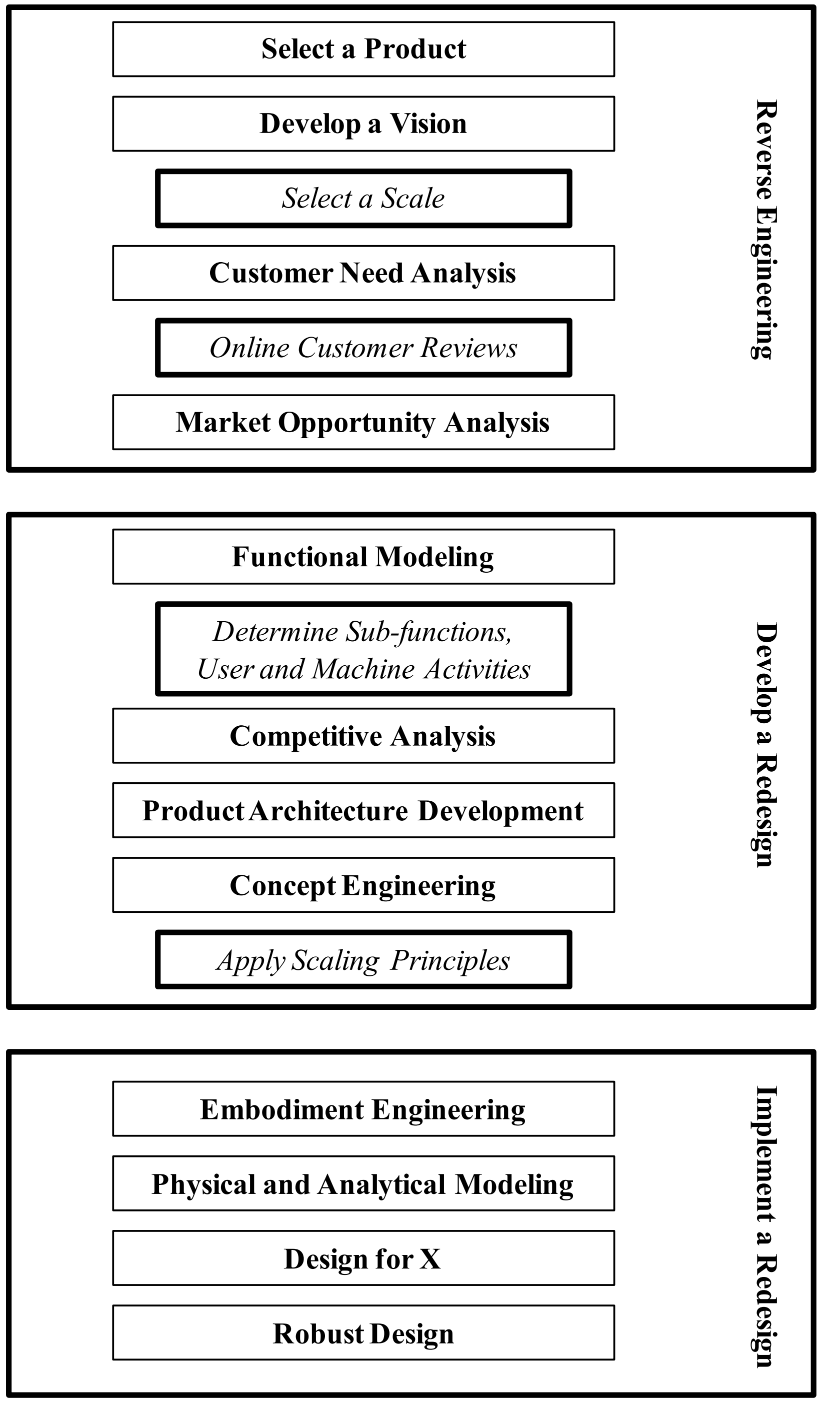


Figure 14: Otto and Wood's redesign product development process (Otto & Wood, 2001) plus additional tasks that must occur to implement the scaling principles properly

‘Develop a redesign’ is the next step which incorporates functional modeling, competitive analysis, product architecture development and concept engineering. The main function as well as the sub-functions are derived within the functional modeling step. This is important for the application of the ‘combine functions’, ‘change method’ and ‘simplify system’ principles. Through an understanding of the products’ sub-functions, the realization that a number of these sub-functions can be combined will be apparent when scaling down. User and machine activities must also be determined for ‘simplify system’ and ‘change method’. Through the creation of an activity diagram, user activities are clearly exposed. This can help reduce the number of user activities involved with handling the product. With these tasks completed, the scaling principles and energy source checklists can be implemented in the ‘concept engineering’ step. This is the proper placement for these principles since the example products are now completely understood and deconstructed. These principles serve as a principle-based idea generation method similar to TIPS/TRIZ, Wordtree and other concept generation aids. The scaling principles should be used in conjunction with these existing idea generation methods in order to generate the most ideas and innovative products.

The last step in the redesign process is ‘implement a redesign’, which incorporates embodiment engineering, physical and analytical modeling, design for X and robust design. This is the proper procedure that must be followed in order to apply the scaling principles. With these steps and scaling principles accomplished, the final concept will fulfill and possibly surpass the design requirements.

3.2.5 Energy Sources

The proper energy source to power a product or system is an important aspect for an engineer or designer to consider. However, choosing the best one that fulfills the design constraints and customer needs can sometimes be difficult. In order to aid this process, two checklists were established that are based on customer needs in conjunction with the "change energy source" principle to help choose the best combination of solutions.

These energy source checklists were derived by observing the example products as well as studying literature about incorporating energy in engineering design (Otto & Wood, 2001). From the example products, it was obvious that energy sources could first be separated into human powered and automatic. Table 4 shows the two energy source checklists, beginning with human powered. This checklist is valuable in determining solutions for a design problem which requires a manual or human powered solution. This is common when a product is scaled down to be hand operated or sold at a cheaper price. A possible design problem which would benefit from this checklist is developing a transportation system for someone who is handicapped. By studying the checklist, one or possibly two mechanisms acted upon by a body part can be chosen to propel the user where they desire.

Table 4: Energy source checklist (Mechanism and energy types based on Otto & Wood, 2001)

<u>Human powered</u>

Body part

- ☐ Arm operated
- ☐ Leg operated
- ☐ Torso operated
- ☐ Neck operated
- ☐ Shoulder operated
- ☐ Knee operated

Mechanism Type

- ☐ Rotational
- ☐ Translational
- ☐ Vibration

Energy Transfer Type

- ☐ Direct
- ☐ Indirect (storage)
  - ☐ Gravity
  - ☐ Pendulum
  - ☐ Spring
  - ☐ Flywheel
  - ☐ Hydraulic accumulator
  - ☐ CAES, pneumatic

Energy Conversion - Electricity

- ☐ Direct
- ☐ Indirect (storage)
  - ☐ Capacitor

Table 4: Continued

<u>Automatic</u>

Energy Type

- ☐ Renewable
  - ☐ Wind
  - ☐ Water
  - ☐ Solar
  - ☐ Geothermal
    - ☐ Direct
    - ☐ Indirect (storage)

- ☐ Electricity
  - ☐ Battery
  - ☐ Plug in
    - ☐ Direct
    - ☐ Indirect (storage)

- ☐ Mechanical
  - ☐ Rotational
  - ☐ Translational
  - ☐ Vibrational

- ☐ Fossil Fuels
- ☐ Acoustic
- ☐ Biological
- ☐ Chemical
- ☐ Hydraulic
- ☐ Magnetic
- ☐ Pneumatic
- ☐ Radioactive
- ☐ Thermal
  - ☐ Direct
  - ☐ Indirect (storage)

The energy produced can be transferred to the product through two methods. The first method is directly, where the rotational, translational or vibrational motion is directly connected to the product. An example of this is a bicycle, shown in Figure 15, where the energy from the user is transferred from the rotating pedals to the rear wheel by a chain.

Figure 15: Direct energy transfer from pedals to rear wheel through gears and chain (Flickr, 2010)

The next method is indirectly, where the energy is stored in a device for future use. These devices can include a spring, flywheel, or hydraulic accumulator. An example of this is seen in Figure 16, a cross bow which stores energy in the flexible bows until it is released when the trigger is pulled at the desired time.

Figure 16: Energy stored in flexible bows until released by trigger (Crankyfarmer, 2010)

Products can also be powered independently, one energy source, or as a combination of energy sources. This typically includes converting human power or mechanical energy into electrical. This is done through the use of a generator which is what performs the energy conversion. Figure 17 depicts a flashlight which is powered by manual action in order to produce and store electrical energy for future use. This type of system it typically used when electricity or an electric source is not available.

Figure 17: Shaking powered flashlight which converts mechanical energy into electric through direct or indirect energy transfer (Geekalerts, 2010)

Automatic systems are more efficient than manual ones due to an increase in power and duration. Due to this, they are typically chosen to power larger products or systems. The list incorporates a number of common automatic power sources which an engineer can choose from. The renewable energy sources are a possible solution for a design problem which is intended for green systems or third world countries. Due to these areas' lack of energy and money, utilization of these power sources could benefit them tremendously. The customer needs and design constraints determine which energy sources to choose. Each category is again capable of utilizing a direct or indirect energy transfer system to power the desired product.

The empirical research approach utilized was helpful in the determination of the scaling principles and energy source checklists. The wide variety of classes and example products aided with understanding and realizing multiple scale differences as well. The scaling principles in conjunction with the energy source checklists and redesign process can improve design efficiency and the original products' performance.

4. COMPARATIVE CASE STUDY

A preliminary test for the scaling principles and revised redesign process is undertaking a comparative case study which involves solving a design problem; designing a portable golf transportation system to carry the user and golf bag. This case study has the ability to validate these principles as a viable idea generation method for product scaling. The following section presents a comparison between the process utilized by a senior design team that solved the design problem previously and the scaling method. The scaling principles are then applied to both example product scales by which ideas are generated and a final design is developed. The final concept is then compared to the senior design teams' concept to understand how the scaling principles affect the overall performance of the design.

The undertaken case study was based on a previous design problem from undergraduate senior design. This problem was previously solved by a team of seniors from The University of Texas Pan-American, which included the thesis author. The proposed problem was designing a portable golf transportation system to transport both the user and golf bag. This design problem was chosen based on the ability to compare the final concepts using a typical design process and the redesign method applying the scaling principles. The comparison can show how the scaling principles affect the number of ideas generated and the performance of the final design. Another reason for choosing this problem is because the scaling principles could be applied in two directions, scaling up from the push cart and scaling down from the golf cart. The last reason for choosing this problem is due to minimal solutions in this desired product scale. The example products must be utilized in order to generate ideas and an overall design.

The customer needs for this design problem are:

- Carry an average size person (190 lbs.)
- Carry an average size golf bag (35 lbs.)
- Securely hold golf bag
- Portable/Compact (fit in average size car trunk, 15 cubic ft.)
- Safe

4.1 Senior Design and Redesign Process Comparison

The previous design method utilized by the undergraduate senior design team was one based on a typical design process. The team based this process on designing an original product, not a redesign of an existing product. This process utilizes similar steps from the reverse engineering method/ scaling design process; however there are also differences. Figure 18 shows both processes in detail.

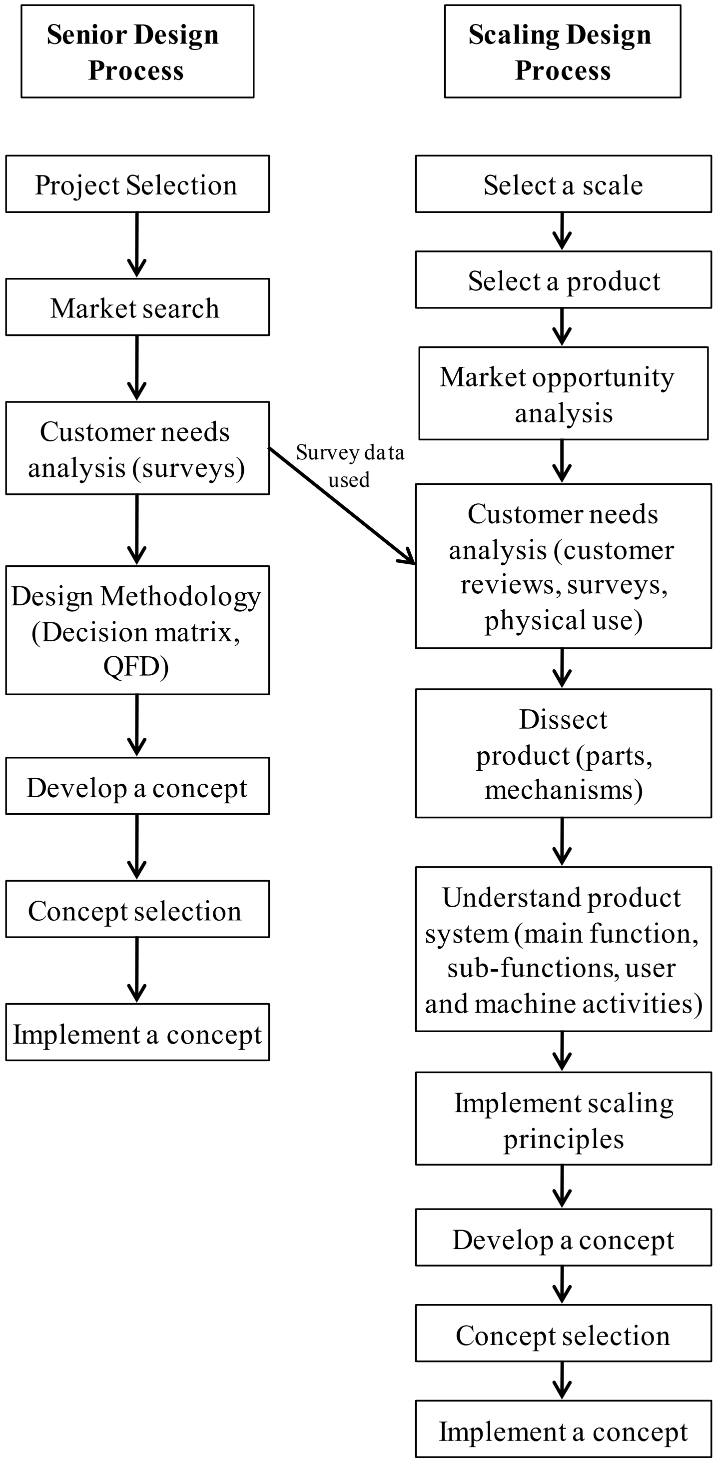


Figure 18: Senior and scaling design process that is based upon the redesign process (Otto & Wood, 2001)

Both processes begin with developing an idea on which the design problem is based upon. In the scaling process, this step incorporates selecting example products as well as the desired scale. The next shared step is market search. This step incorporates researching other products and designs in order to understand what is currently on the market and whether there is a need for such a product. Next, a customer needs analysis is performed to determine whether users would purchase such a product and if they did what they would like in the product. This is performed through surveys, interviews and other similar methods. The senior design process utilized surveys which were passed out at local golf courses in order to determine if such a product is wanted. This survey can be seen in the Appendix G. The results from this survey were also utilized in the scaling process for better understanding customer needs and wants. For the scaling process, additional online customer reviews were researched on the example products to further aid in understanding customer likes and dislikes. This additional step was performed due to the redesign process.

The senior design process continues to design methodology, including a decision matrix and quality function deployment. The decision matrix aided in comparing the customer wants to determine which was most important, Appendix H. The QFD table correlates wants to engineering specifications or requirements in order to establish targets in which can be met. The next step in the senior design process jumps to idea generation or develop a concept. The method utilized by the senior design team to generate concepts was based on an overall picture. A complete concept was developed which limited the amount of ideas generated. Very few ideas were specific to parts and mechanisms which differed greatly to the scaling process. Due to the close observations of the scaling products, a lot of ideas were generated for specific parts and features. This again is due to the scaling principles and the focus on the scaled product.

The scaling process continues with understanding the example products. These products are researched and deconstructed in order to fully understand how they work. This includes physically studying, examining, and tearing the example products apart. Each example product is decomposed into sub-mechanisms followed by individual parts. The main function, sub-functions as well as machine and user activities are also determined in order to take full advantage of the scaling principles. Once the product is fully studied, the scaling principles can be applied to all aspects of the example products; sub-functions, parts, user and machine activates. The scaling principles are applied within the idea generation step. This step can also utilize additional idea generation methods such as mind maps and TRIZ to gain supplementary ideas. From this step on, both processes incorporate the same design and development steps. These include develop a concept, concept selection and implement a concept. The scaling process is similar to the typical design process; however additional detailed actions must be taken to implement the principles correctly.

4.2 Small Scale

Due to the desired scale, in between two distinct product scales, the principles can be applied in two directions. The scaling method is first applied to the small scale products followed by the application of the principles and details on the generated ideas.

4.2.1 The Scaling Method with Small Scale Products

Following the redesign process, choosing the best scaling products was the first step. Due to developing a design from two different scales, the small scale products were looked at first. The products chosen from this category are manual and electric push carts. Both manual and electric carts were picked to scale from in order to fully understand this product class. Both have their advantages and disadvantages that are taken into account to develop the best design possible.

An internet search was performed in order to find these products. Using Google search, searches were made for 'golf push carts' and 'electric golf push carts'. This led to websites such as Golfsmith.com, Thesandtrap.com and Criticalgolf.com which provided many variations of carts as well as their customer reviews. These reviews proved valuable in understanding what customers liked and disliked about their push carts. The scaling products reviewed were the Clicgear Model 3.0, Sun Mountain 2010 Micro cart and Tour Trek Tahoe push cart, all seen in Table 5. The Clicgear and Tour Trek models both have three wheels while the Sun Mountain model has four, the two typical configurations in design for push carts on the market. Based on the reviews from *Golfsmith.com*, the Clicgear and Sun Mountain carts were the highest ranked with almost 5 stars (Golfsmith, 2011). Table 5 also shows what features and aspects of the scaling carts are liked by the customers. This is taken into great consideration when generating ideas for the final concept.

Table 5: Scaling Manual Push Carts (Golfsmith, 2011)

 **Clicgear Model 3.0 (Golfsmith, 2011)**	**Specifications** • 3 wheel design • Foam tires • 3 hinging points • Folding rear wheels • Elastic bungee straps • Hand brake • Accessory console • $200	**Likes** • Folded size • Easy to use • Easy to collapse • Stability • Good value • Quality • Accessory holder **Dislikes** • N/a
 **Tour Trek Tahoe Cart (Golfsmith, 2011)**	**Specifications** • 3 wheel design • Plastic tires • 1 hinging point • Folding rear wheels • Velcro golf bag straps • Foot brake • Accessory console • $100	**Likes** • Lightweight • Good value • Easy to use **Dislikes** • Folded size • Instability • Poor design

Table 5: Continued

	Specifications	Likes
 **Sun Mountain 2010 Micro Cart (Malleast, 2011)**	• 4 wheel design • Foam tires • 2 hinging points • Sliding rear wheels • Adjustable golf bag brackets • Hand brake • Accessory console • $200	• Folded size • Easy to use • Easy to collapse • Stability • Good value • Quality • Accessory holder **Dislikes** • N/a

In order to better understand the way these products are engineered, the Tour Trek Tahoe cart was physically obtained and studied. A picture of this cart can be seen in the appendix. This physical interaction allowed the author to test the performance of the cart in action. The first step undertaken was examining the cart for dimensions and parts. This cart is perceived as one of the most basic push carts on the market. The design is very simple with only three wheels, one hinging point, and minimal accessories. Due to this and the aluminum frame, the cart only weighs 11 pounds. A parts list was also determined to view and understand how it is assembled and operates, Appendix D. This list can be seen in the appendix. This cart unfolds by lifting the handle until a locking clamp slides into the proper position. Once there, the user must tighten the knob to secure the handle in its upright position. This cart utilizes Velcro straps on both the lower and upper supports to secure the golf bag in place. The only accessory this cart contains is a plastic console to hold two golf balls, the score card and small personal items.

The electric push golf carts selected are the Bag Boy Navigator Electric Cart and the Sun Mountain Speed E Cart, depicted in Table 6. These carts are powered by batteries and an electric motor for propulsion. They are operated by a user controlled panel/handle that controls speed and even how far to travel ahead of the user to the desired spot. Both carts also include an override to disengage the wheels from the motor in order to push the carts manually if the batteries die. A product review from The Sand Trap also proved valuable in determining what is liked in these electric carts. This includes the small compact size when folded, long battery life and easy setup (Sand Trap, The, 2011).

Table 6: Scaling Electric Push Carts (Sand Trap, The, 2011)

 **Bag Boy Navigator Electric Cart (Sand Trap, The, 2011)**	**Specifications** • 4 wheel design • Foam tires • 3 hinging points • Velcro straps • Two 140-watt electric motors • 9-volt battery • Remote control • Disengage rear wheels • $1500	**Likes** • Folded size • Convenient • Easy setup • Stability • Long battery life • External remote control **Dislikes** • No accessories • Controller issues
 **Sun Mountain Speed E Cart (Sand Trap, The, 2011)**	**Specifications** • 3 wheel design • Air filled tires • 2 hinging points • Adjustable golf bag brackets • 1 24-volt hub motor • 12-volt battery • Hand brake • Accessories	**Likes** • Folded size • Convenient • Easy setup • Stability • Long battery life • Adjustable handle • Accessory holder **Dislikes** • N/a

Continuing with the reverse engineering design process, the main function of these push carts was determined to 'transport golf bag', whether it be user powered or battery powered. Black box models were derived for both categories of push carts to better understand their functionality. These models can be seen in Figure 19 and Figure 20.

Figure 19: Manual push cart Black Box model

Figure 20: Electric push cart Black Box model

Both manual and electric push carts have identical material and signal input and outputs. The differences between the two are seen in the energy input and output flows. The manual push cart includes human energy as the input and kinetic energy as the output. The electric push cart adds electricity and human energy as inputs and sound, kinetic energy and heat as outputs.

With the overall function of both manual and electric push carts obtained, sub-functions as well as user and machine activities were determined, Table 7 and Table 8.

Table 7: Manual push cart sub-functions

- **Expand to full size**
  - Pull out legs and handle - user activity
  - Slide and tighten locking clamp- user activity
- **Hold golf bag**
  - Strap in golf bag (Velcro)- user activity
- **Transport golf bag around course**
  - Push and pull of cart- user activity
  - Push and release parking brake- user activity
- **Fold to compact size**
  - Loosen clamp and slide up- user activity
  - Pull legs and handle together - user activity

Table 8: Electric push cart sub-functions

- **Expand to full size**
    - Pull out legs and handle- user activity
    - Tighten locking clamp- user activity
    - Place in battery and connect- user activity
- **Hold golf bag**
    - Strap in golf bag (Clip)- user activity
- **Transport golf bag around course**
    - Throttle control- user activity
    - Cart propulsion- machine activity
    - Press and release parking brake- user activity
- **Fold to compact size**
    - Disconnect and remove battery- user activity
    - Loosen clamp- user activity
    - Pull legs and handle together- user activity

Deriving these product sub-functions and user or machine activities are important within this scaling process. The principles, such as 'simplify system' and 'combine functions', require these aspects of the product to be fully understood in order to take full advantage of idea generation.

Activity diagrams were also derived to better understand the tasks that can be performed by the user. These actions are also helpful in determining other possible functions the product could perform. Figure 21 shows both of these activity diagrams with areas that are applicable for two of the scaling principles.

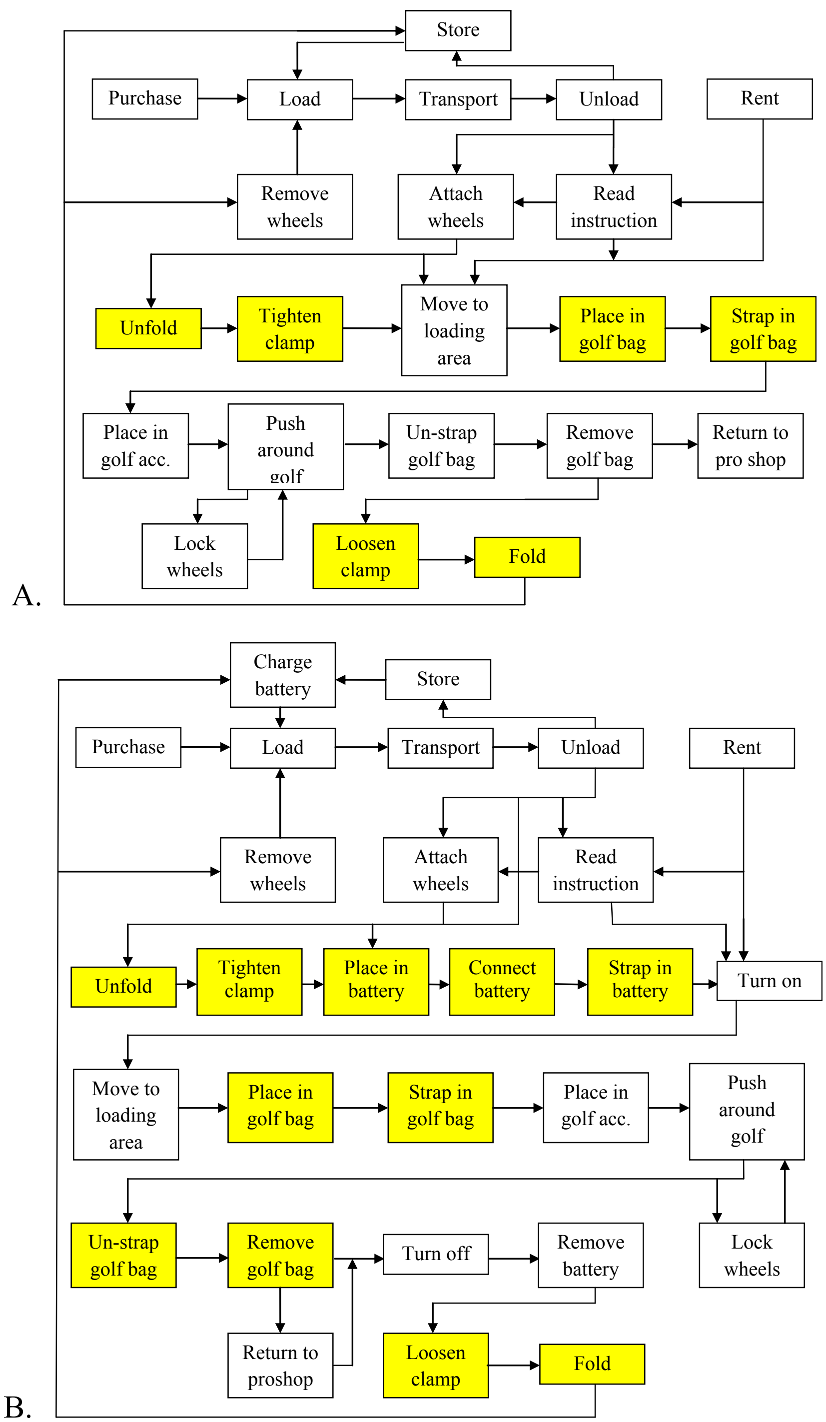


Figure 21: A. Manual and B. Electric push cart activity diagrams with highlighted boxes that represent possible activities that can be simplified or combined through the application of the 'simplify system' and 'combine functions' principles

4.2.2 Small Scale Principle Results

With the small scale products now fully studied and understood, the derived scaling principles were applied. Each principle is applied to every aspect of the product including product sub-functions and activity diagrams. Customer needs and wants are also taken into full consideration. Beginning with the manual push cart, the 'change energy source' principle in conjunction with the energy source checklist helped determine possible solutions. The human powered checklist proved that multiple combinations of body parts, mechanism types and energy transfer were possible. A more suitable solution derived is based on a tricycle design which allowed for the user to sit and pedal with either their legs or arms, as depicted in Figure 22. This design would incorporate a rotational mechanism to transfer the energy directly to the wheels to transport the user and golf bag around the golf course, similar to a bicycle. These designs could utilize multiple wheel configurations; including 2, 3 or 4 wheels. Other possible ideas included a scooter based cart that is powered by the users' legs.

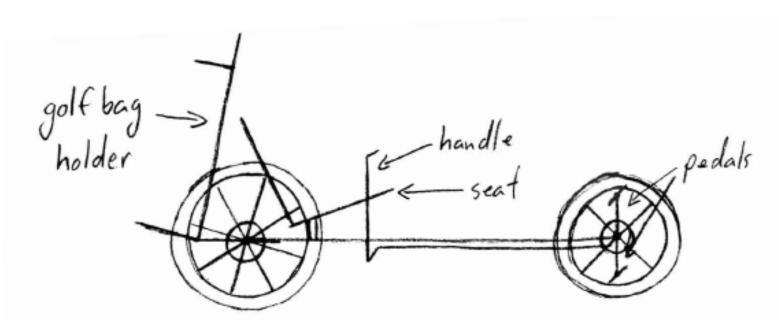


Figure 22: By applying the energy source principle and human powered checklist, a sitting tricycle design was generated that is powered by the user

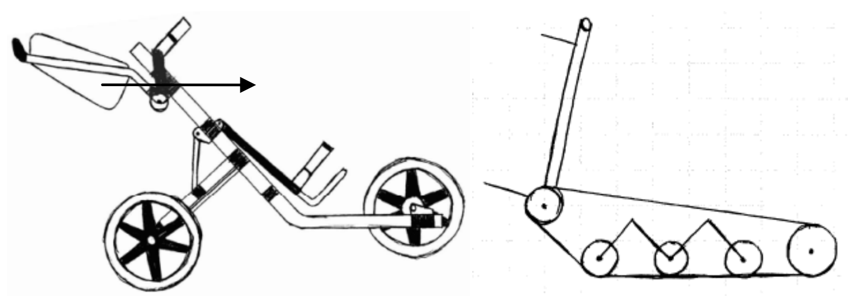
The automatic energy checklist also proved valuable in determining other possible solutions. Beginning with the renewable energy types, wind and solar were the two that were best suited for this application. One possible design with solar energy would be to incorporate solar panels onto the product to charge the onboard batteries. Electricity and gasoline are other popular solutions to many vehicle design problems. Fossil fuels would incorporate a small gasoline engine to power the cart around. Current full sized golf carts incorporate gasoline engines; however with the current gas prices and sound these engines make, this idea is not fitting. An electric version would use rechargeable batteries and an electric motor for power, similar to that of the electric push carts. This is more suitable due to the amount of power produced and quietness of the motor. A more extreme idea would be to use electricity and magnetic forces to power the vehicle, similar to magnetic levitation trains. This would not be suitable due to all the changes required by all golf courses to accommodate this product.

The 'simplify system' principle was next applied. Due to the design of these manual push carts, they are already simplistic in terms of their functions and parts. Customer needs and wants are what led to these solutions. However, after studying the activity diagram, functions, parts list and customer needs and wants, possible ideas were determined. These ideas are based on keeping the entire design simplistic due to the needs and wants of being compact, lightweight and easy to use. The first idea involves simplifying the unfolding and folding process by removing the user's activity to tighten/ loosen clamp to keep the cart in the upright position. A minimal number of steps and parts are what is desired for this process as well as folding the cart back up. This can be seen in Figure 23, the Bag Boy automatic unfolding cart. This product only requires the user to lift up on a handle in which the cart unfolds and automatically locks into the upright position. This process removes unnecessary user activities and keeps setup time short.

Figure 23: The 'simplify principle' in conjunction with customer reviews revealed that a one step unfolding process is preferred, similar to this product (Bagboy, 2011)

Securing the golf bag should also be simplistic in design, with minimal steps and parts. Focusing on the user activities again, the strap in golf bag activity can be removed. This will reduce the number of user activities to just one. Considering the number of wheels, with the correct stance/width, three wheels are sufficient enough for a stable product without the added weight and support of a fourth wheel.

‘Change method’ is the next principled applied. The main function, transport golf bag, can be changed by altering its method. The original method incorporates a supporting frame with free spinning wheels that is pushed and guided by the user, Figure 24. By applying the sub-principle ‘change user activity to a machine activity’, alternate means incorporate an automatic power source. A remote control can be utilized to tell the cart where to go or to automatically follow the user through sensors on the cart and user. Another idea is to remove the original wheels and incorporate a track system, similar to tanks, which will allow the cart to traverse various terrains, allowing the cart to cross muddy and wet areas. This design idea is also presented in Figure 24 below. A hovercraft design is another possible idea that can be utilized.



A. B.

Figure 24: A. Original cart wheel design B. Converted to a track system used to transport the golf bag and user realized due to the ‘change method’ principle

The first sub-function of the manual push cart is to 'expand to full-size' which is performed manually by the user by unfolding and locking it into place. This can also be changed to a machine activity through hydraulic pistons or electric motor. Another idea is to utilize a shape memory material that 'remembers' its unfolded shape and when activated, returns to that shape. This was realized by applying the sub-principle 'adapt existing system'. Various ideas were then derived for ways to secure the golf bag. Some ideas include utilizing elastic straps like bungee cords, Velcro, magnetic locks and even automatic self-tightening straps. Figure 25 depicts an adjustable bracket idea that can also be utilized to secure the golf bag onto the cart. For folding, the user again must loosen all knobs and manually fold the cart. Ideas for this sub-function are the same as the unfolding process previously mentioned. Ideas for the emergency brake include a foot applied system, hand lever system, or even an automatic setup which is automatically performed once the cart comes to a complete stop.

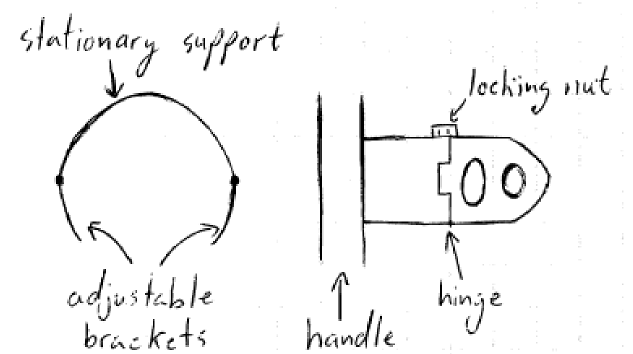


Figure 25: The 'change method' principle also led to possible golf bag securing ideas such as adjustable brackets that are only adjusted once

The next principle, ‘combine functions’, is again applied to the activity diagram. First, transport golf bag and transport user can be combined into one product. This idea has numerous advantages. Because the user will not have to exert energy pushing the golf bag cart or carrying the golf bag, energy will be saved. This increases the users focus and energy into playing better golf. The next idea combines unfolding the cart and locking it into place. This user activity can be transferred into a machine activity through automatic locking clamps or pins. This reduces the user activity allowing for an easier means of use and quicker setup time. Another area where activities can be combined is placing the golf bag in the cart and securing it in place. This can be combined by utilizing an automatic securing system such as magnets or ideas from the ‘change method’ section.

‘Directly transfer components’ was next applied to the manual push carts. Due to the change of scale, many parts and features have to be altered; however there are some features that are not changed and can be reused. The scale change incorporates making the proper alterations to accommodate transporting the rider and golf bag. Since the golf bag is not changing scale, the various securing systems from the scaling push carts can be transferred. This includes the Velcro straps, bungee cords and adjustable brackets. Due to many of the golf accessories also remaining unchanged, console features can also be used. Possible features include the golf ball, tee, score card and drink holders. Due to the design problem, specifically the compact aspect, the folding mechanisms can also be transferred to aid in fulfilling this need.

The last principle, ‘change parameters’, is an important principle to consider since the product is altered to now support the weight of the user. This additional force on the product means changing the extensive properties, materials and dimensions. The current aluminum frame needs to be changed to a stronger aluminum alloy or lightweight steel alloy. One possible material is 4130 chromoly steel. It is an alloy steel with a high strength-to-weight ratio. Besides the frame’s material, other material changes were taken into account. An example of this is the possibility of changing plastic pieces to carbon fiber for its added strength while still remaining lightweight. The wheels and tires is another place where material changes can be made. The rims also need to be altered for the increased load but can still remain light due to new available materials.

Parameter change also includes the changes in the physical placement of the components as well as possible additions. Beginning with the wheels, various configurations are possible. This includes the possibility of using three or four wheels. For a three wheel vehicle, there are two possible combinations. The first is having one wheel in front and two in back while the other is two in front and one in back. These different configurations can be seen in Figure 26 below.

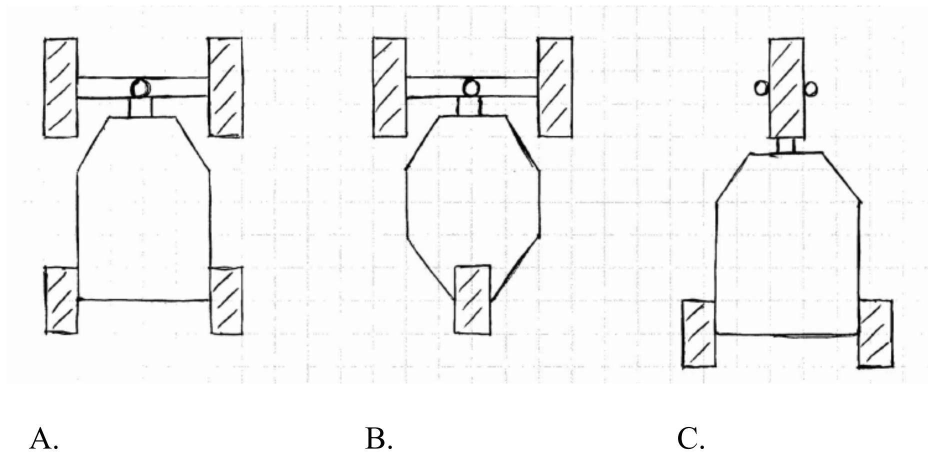


Figure 26: The 'parameter change' principle revealed these possible cart configurations based on A. Four and three wheel setup with B. Two wheels in front or C. One wheel in front

Due to the new need of transporting the user, a platform needs to be added to the final design. This is one feature that is not found in the scaling products. The golf bag position on the cart can also be altered from the original design. The bag position can be placed in the front; rear or side of the cart depending on what is most stabile. Other possible component variations include the location of the brakes and the position of the handle.

The principles were next applied to the electric push cart in the same manner. Many ideas and design considerations are similar to the manual push cart with slight modifications. Beginning with 'energy source', due to the original design already incorporating batteries and electric motors, human power was removed. This is due to a decrease in the efficiency of the product. However, all automatic energy ideas are transferred over to this product design process. From product research, not one electric push cart was found that utilized solar panels to charge as it was in use, Figure 27. This feature would increase battery life if the user was using the product on sunny days, which is typical weather for playing golf.

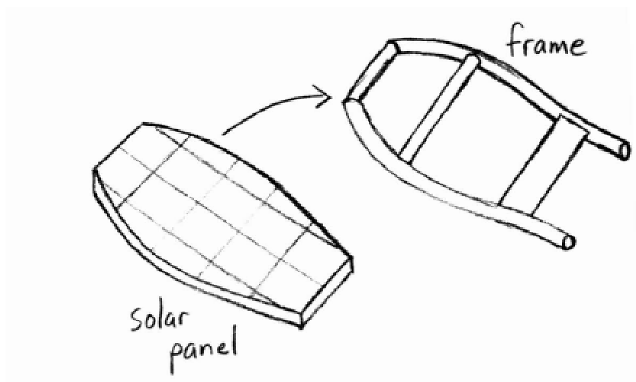


Figure 27: Solar panel idea incorporated onto the base of the cart frame through 'energy source' principle

Next, the 'simplify system' principle again led to keeping the number of user activities and parts minimal just like the manual push cart. Keeping the design simple is the main priority for ease of use and weight. Starting with the power sources, the number of batteries and motors should be kept to a minimum while still performing properly. One battery and motor would be the optimal design for weight consideration. The Bag Boy cart utilizes two motors which power each wheel; this can be simplified to one that drives both wheels. The driving mechanism should also simple in design, requiring only the minimal number of parts but still durable. The electric push cart contains some extra accessories that can be removed or simplified. One of these is the remote control with its additional mechanisms for operation. This feature is considered to be a customer want not a need. With this removal, several steering mechanisms can be removed, saving weight.

‘Change method’ ideas are again all transferred over from the manual push cart since there are many similarities. This includes the minimal step and parts involved with the unfolding and folding process. It also includes the various ideas for securing the golf bag onto the cart.

For ‘combine functions’, again ideas are shared from the manual push cart. A new idea with this specific cart involves combing the battery placement in the cart and plug in. These two steps can be incorporated into one through a battery with prongs that automatically make the electrical connection. This design would be similar to a cell phone battery with its metallic prongs, as seen in Figure 28.

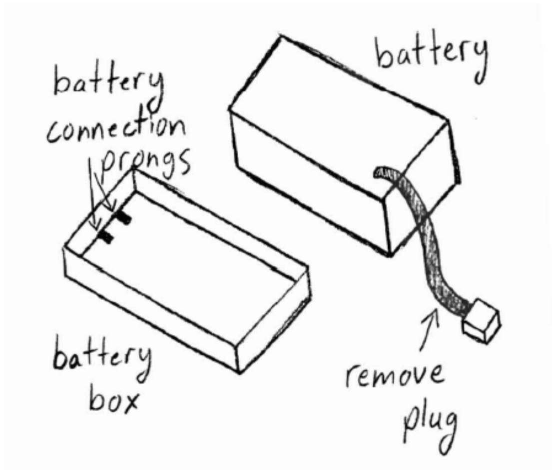


Figure 28: Combining battery placement into cart and battery plug in by utilizing metallic connection prongs, remove user plug

This electric push cart is similar in scale to the required design problem. For ‘directly transfer components’, the same ideas are shared from the manual push cart. This includes the golf bag securing mechanism and the accessory console features. Additional features that can be transferred include the disconnect mechanism between the motor and the rear wheel. This will allow the cart to be pushed with less effort in case the batteries die.

‘Parameter change’ again plays an important role in this new design. As explained with the manual push cart, the added weight of the user adds an extra load that must be accounted for. Changes in the materials and scale must be made to sustain these increased stresses. The battery and motor placement can also be altered for optimal design. For stability, the majority of the weight should be kept low for a low center of gravity. The position of the motor can also be placed in the front or rear of the cart depending on if it's a front or rear wheel cart. A front wheel cart could possibly incorporate the motor in the hub of the wheel. A rear wheel drive cart is favored due to its ability to push instead of pull and its increase in traction. Table 9 depicts a summary of all ideas generated from the scaling principles applied to the manual and electric push carts.

Table 9: Push cart idea summary generated from scaling principles

Principle **Sub-principle**	**Generated Ideas**

Change Energy Source/ Energy Check List	• Human powered
	  o Sitting tricycle
	  o Standing scooter
	• Automatic
	  o Solar panel
	  o Wind sail
	  o Electric motor
	  o Gasoline motor

Simplify System
'Remove user activities and parts'
	• Simplify unfolding process
	  o Remove 'tighten clamp' user activity
	• Simplify securing golf bag
	  o Remove 'strap in golf bag' user activity
	• Remove/ minimize additional parts
	  o Number of wheels
	  o Minimize number of batteries and motors

Table 9: Continued

	○ Remove remote control with additional driving parts ○ Remove accessories
<u>Change Method</u> **‘Change a user activity into a machine activity’** **‘Adapt existing system’**	• Transportation ○ Change to machine activity ▪ Electric or gasoline motor ▪ Remote controlled ▪ Track based drive-train ▪ Hovercraft drive-train • Unfold ○ Change to machine activity ▪ Hydraulic pistons or electric motor ○ Adapt existing system ▪ Shape memory alloy • Secure golf bag ○ Velcro straps ○ Bungee cords ○ Magnetic locks ○ Automatic self tightening straps ○ Adjustable brackets • Emergency brake ○ Hand lever ○ Foot lever ○ Automatically applied once stopped
<u>Combine Functions</u> **‘Combine user activities’**	• Transport golf bag and user • Combine user activity ○ Unfolding cart and locking in upright position w/ automatic locking clamps/ pins

Table 9: Continued

	o Place and secure golf bag
	    ▪ Automatic straps
	    ▪ Flexible brackets that fit to shape of bag
	o Placement of battery and plug in
	    ▪ 1 step process, remove plug in

<u>Directly Transfer Components</u>	• Golf bag securing mechanisms • Accessory console features • Folding mechanisms • Motor and rear axle disconnect

	• Materials
	    o Stronger aluminum frame
	    o Lightweight chromoly steel frame
	    o Carbon fiber brackets
	    o Aluminum wheels
	• Increase scale
	    o Frame thickness and diameter
	    o Wheels and tires
	    o Supporting brackets
	• Position
	    o Wheel configuration
	        ▪ 3 or 4 wheels
	        ▪ 1 or 2front tire
	    o Golf bag- front, rear, side
	    o Rider
	        ▪ Standing
	        ▪ Sitting

Table 9: Continued

	○ Handle ▪ Front ▪ Sides ○ Brakes ▪ Rear ▪ Front ○ Motor ▪ Rear- rear wheel drive ▪ Front- incorporated into wheel hub, front wheel drive

4.3 Large Scale

The scaling method and principles are next applied to the large scale product, electric golf cart. The process and generated ideas are described in detail in the following sections.

4.3.1 The Scaling Method with Large Scale Products

Scaling down from a larger scale was also performed in order to understand both sides of the product scale. The large scaling product chosen for this problem is an EZGO TXT electric golf cart ($5000) (EZ GO, 2011), depicted in Figure 29. This is a well-known and typical golf cart used at golf courses that users rent on a daily basis. An internet search was performed for customer reviews through Google search by using ‘ezgo golf cart review’ in the search field. Websites such as Golfcartcomparison.com and Cartaholics.com forum proved valuable for understanding customer needs and wants as well as their likes and dislikes of the cart. From reading these reviews, there were many features and aspects of this cart that customers liked. These include powerful, fast, comfortable, easy to drive, durable, long battery life and plenty accessory storage space, (Cartaholics, 2011). There were not many negative comments on this cart. The few include expensive maintenance, some battery problems and when rented at golf courses, the price. These reviews helped realize what customers want in an electric golf cart design.

Figure 29: EZ GO TXT electric golf cart (Batterysource, 2011)

The EZGO website was utilized to obtain specifications of the carts components and features. The service parts manual was also used to understand the design of the cart and how it works (Ez Go, 2011). It proved valuable in determining all components associated with its design. This type of golf cart is powered by an electric motor with rechargeable batteries, unlike other models which use a gasoline motor. Due to the carts size and parts, the weight exceeds 900 lbs. with the addition of the six batteries.

A black box model, function list and activity diagram were also derived for this full size golf cart. The function of this cart is to 'transport user and golf bag', as seen in Figure 30. The energy inputs for this product are electricity, hand motion and foot motion.

Figure 30: Electric Golf Cart Black Box Model

Next, the sub-functions as well as the user and machine activities are presented for this electric golf cart below in Table 10. This helps in understanding how the golf cart functions and sub-functions are performed.

Table 10: Electric golf cart sub-functions

- **Load golf bag**
    - Lift and place golf bag onto cart- user activity
    - Strap in golf bag (lever clip)- user activity
- **Transport golf bags and passengers around golf course**
    - Throttle control- user activity
    - Cart propulsion- machine activity
    - Press and release brake- user activity
- **Unload golf bag**
    - Un-strap golf bag- user activity
    - Lift and remove golf bag from cart- user activity

Finally, the activity diagram is presented in Figure 31 in order to understand all possible tasks performed by the user.

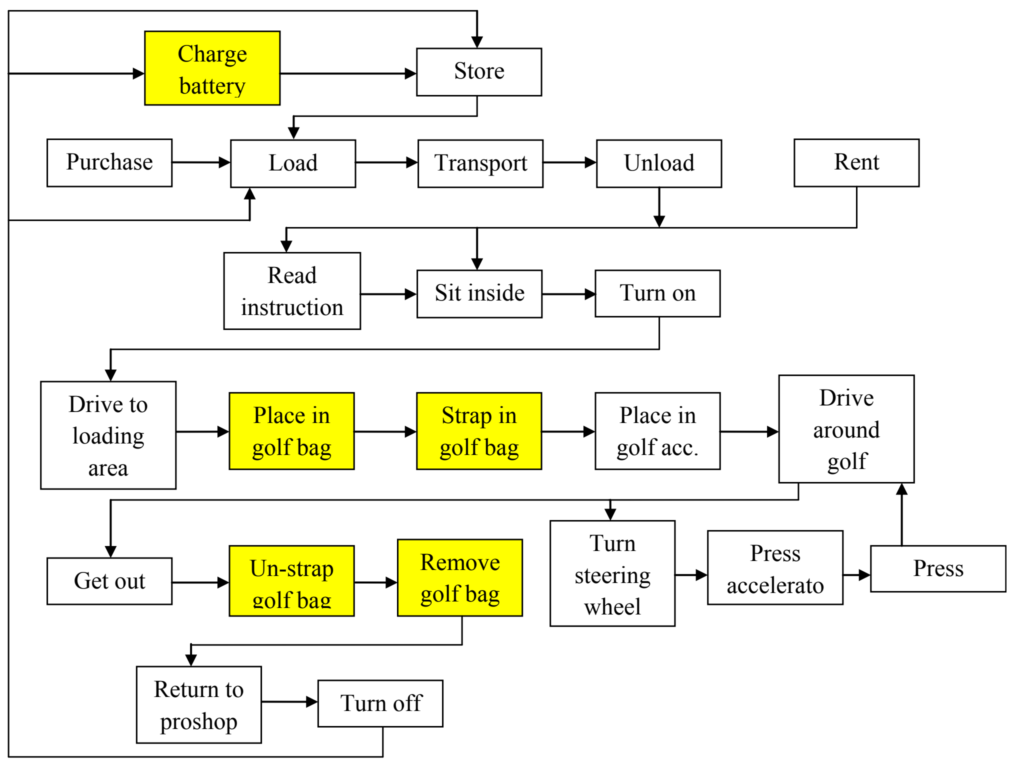


Figure 31: Electric Golf Cart activity diagram with highlighted boxes that represent possible activities that can be simplified or combined through the application of the scaling principles

4.3.2 Large Scale Principle Results

For power, the EZGO golf cart utilizes 6 8-volt batteries with a 48-volt DC electric motor. Due to this original power source, this product will decrease in efficiency if converted over to a human powered design. Human energy is not as efficient as an electric motor due to the minimal amount of energy produced in the short amount of time. Thus other automatic power sources, such as the ones previously described with the manual push cart, solar panel and electric motor can also be utilized for this design.

All automatic power source ideas will be suitable for this design problem, including solar panels. Figure 32 depicts a possible layout of the motor and batteries located in the base of the cart with the solar panel located on top.

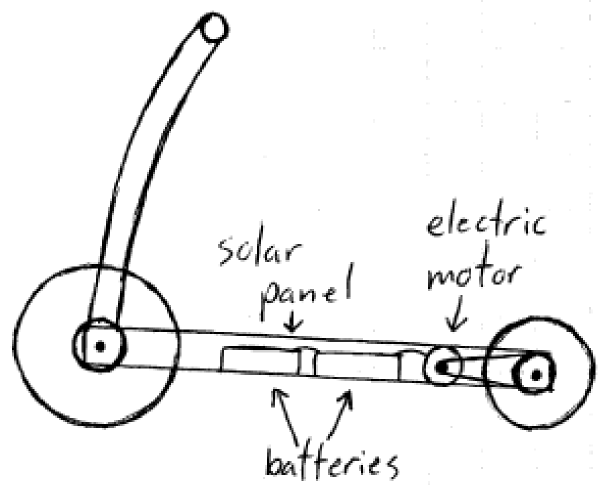


Figure 32: Possible configuration of an electric motor with batteries and solar panel derived from the 'energy source' principle and automatic energy source checklist

The new design problem is to transport one user and one golf bag. Due to the carts original capability of transporting two users and two golf bags, many parts and features can be removed or simplified. To begin, the body of the cart can be altered. This consists of all body panels and parts required to hold it in place. They can either be completely removed or minimized in scale to only cover only what is important, such as the batteries, motor and moving parts. Accessories can also be removed or minimized, such as the roof, windshield, bench seat, accessory basket and instrument panel. All these ideas will minimize the overall weight of the vehicle as well as its physical size. This cart also utilizes many components that can be simplified. First, the number of batteries can be reduced as well as the onboard battery charger which is not a necessity. An external charger can be used in place of this for recharging the onboard batteries.

Next, the drive-train and suspension can be altered due to its complexity. This includes converting the front leaf springs which are large and heavy to a lighter more compact system, such as a coil-over suspension. The rear suspension can also possibly be converted to coil-over's or removed completely. In this case, the rear tires can provide enough absorption to compensate for the lack of suspension. When observing the wheels and tires, one wheel can be completely removed to make a three-wheel cart and/or the wheels can be made smaller and lighter. The rear drum brakes can also be simplified into a manual disc brake setup, removing many small internal parts and heavy drum rotor. This original design is again complex and large, features that are trying to be minimized or simplified. The current steering mechanism is a rack-and-pinion setup including the steering wheel, tie rods, linkage and spindles. This mechanism can be simplified into a simple go-kart style steering, removing the complicated rack-and-pinion. The steering column can directly rotate the tie rods, in-turn rotating the spindles and the wheels. The rear axle is the last drive-train mechanism that can be simplified by converting it into a solid axle system, removing the necessity of a differential and the axle housing. This idea can be seen in Figure 33 with the necessary belt pulley, wheel and axle. Other parts that can be simplified include the accelerator, direction selector, electrical system and the parking brake system. These features and components are again complex, simpler designs are available to use which better fulfill the design problem.

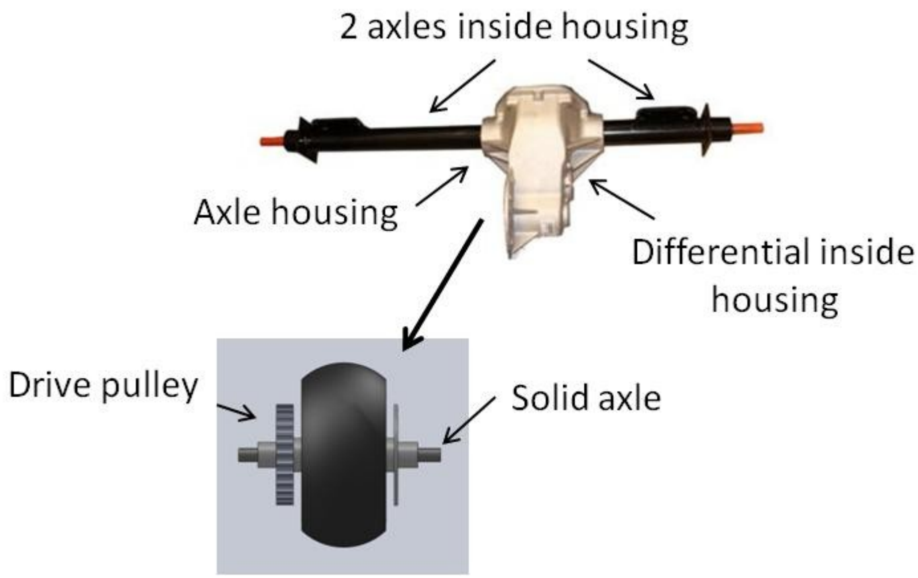


Figure 33: Original rear housing with axles and differential simplified to a solid rear axle design with incorporated brake and pulley grasped through the application of the 'simplify system' principle (Ezgo, 2011)

The 'change method' principle is applied to the golf cart functions, sub-functions and its various mechanisms. Possible ideas for the transport function are similar to the manual and electric push cart including a track system and magnetic levitation system. As previously mentioned, the suspension can be converted into a rubber, coil-over or airbag system with a multitude of suspension geometries and setups. These include

Macpherson, double-wishbone, trailing arm and twin I-beam suspension types. These suspension types can be adapted to final design from the original vehicle models. A simple rigid, shock absorber and Macpherson style suspension ideas are shown in Figure 34.

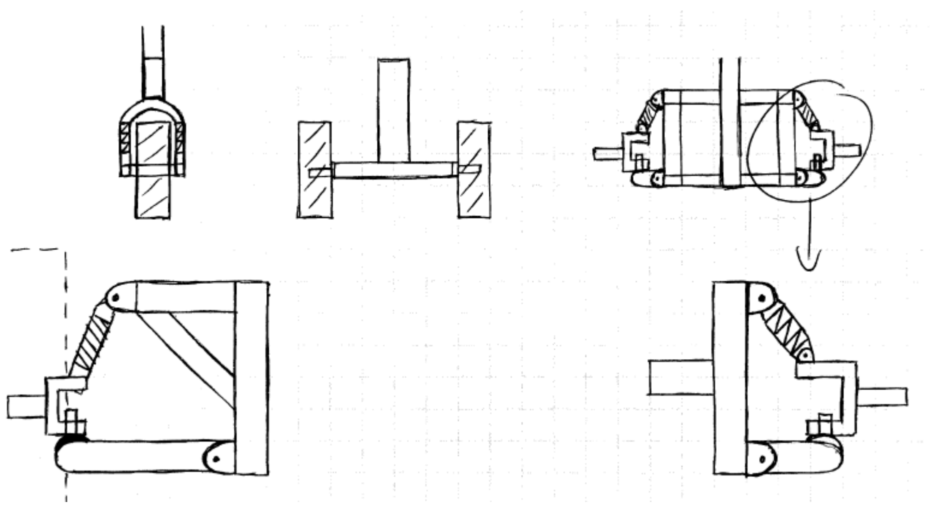


Figure 34: Potential suspension and steering configurations derived by applying the 'change method' principle

Accelerating and braking operations can be changed from foot operated into hand and use a mechanical cable instead of electrical signals. For securing the golf bag in place, again ideas from the small scale products can be utilized, such as the bungee cords or magnetic locks. These were taken from the 'simplify system' and 'change method' principles. Rider position is another aspect that can be changed. The sitting position can be changed to standing by incorporating a removable seat depending on the rider's preference. The overall length of the cart can be shortened due to this change.

Only one idea was derived for 'combine functions'. This involves braking and applying the parking brake. The original cart uses a brake pedal with an additional pedal/lever to apply the parking brake as seen on Figure 35. This can be combined into one simple motion and mechanism instead of two. The idea incorporates pressing the brake pedal to slow down and once at a complete stop, the parking brake is automatically applied.

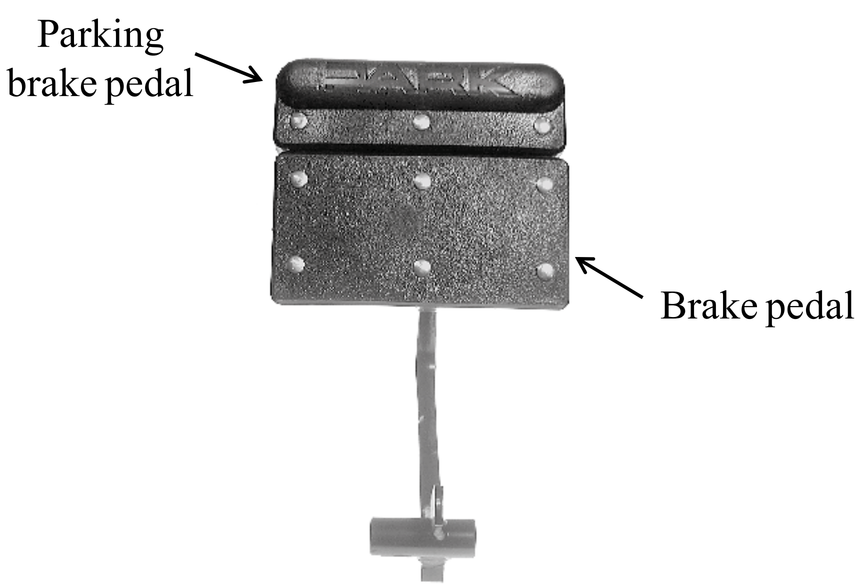


Figure 35: Golf cart brake and parking brake pedal (Ocmonstercarts, 2011)

The scale of the original golf cart and the desired scale for the design problem are quite drastic. Due to this, the 'directly transfer components' principle did not reveal many new ideas. The only feature that could be transferred was again the golf bag securing mechanism. In this case, the cart utilizes a clamp which securely holds the strap and golf bag in place.

Due to this scaling down process, material properties and physical dimensions are minimized. To begin, due to a lighter load, the frame rails can be smaller in diameter and changed to a lighter material. Possible materials again include aluminum or light weight steel. The body can again be made smaller and lighter by using materials such as carbon fiber or lightweight plastic. These materials are still durable but weigh dramatically less. All drive-train and suspension parts can also be scaled down due to the lighter loads and smaller forces. These include control arms, tie rods, spindles, wheels, brakes, motor and rear axle. These scaled down parts will also dramatically decrease the overall weight of the final design, fulfilling the customer need. Table 11 depicts a summary of all ideas generated from the scaling principles applied to the full size electric golf cart.

Table 11: Golf cart idea summary generated from scaling principles

Principle **Sub-Principle**	**Generated Ideas**
Change Energy Source/ Energy Check List	• Automatic ○ Solar panel ○ Electric motor ○ Gasoline motor
Simplify System	• Remove/ minimize number of parts

Table 11: Continued

<table>
<tr><td>'Remove and/ or minimize parts'</td><td>

Body panels
Cover important and moving parts
Accessories
Roof
Bench seat
Instrument panel
Batteries
Onboard charging system

Suspension
Remove rear suspension
Steering
Remove rack-and-pinion steering
Brakes
Remove heavy and big drum brakes
Rear axle
Remove differential and axle housing
Single axle w/ drive pulley
Secure golf bag
Number of wheels

</td></tr>
<tr><td><u>Change Method</u>
'Adapt existing system'</td><td>

Transportation
Adapt existing system
Remote controlled
Track based drive-train
Hovercraft drive-train
Suspension
Adapt existing system
Macpherson

</td></tr>
</table>

Table 11: Continued

	▪ Swing axle ▪ Double-wishbone • Secure golf bag o Adapt existing system ▪ Velcro straps ▪ Bungee cords ▪ Magnetic locks ▪ Automatic self-tightening straps ▪ Adjustable brackets • Brake and throttle o Hand lever o Foot lever o Automatically applied once stopped
<u>Combine Functions</u> **'Combine separate parts'** **'Combine user activities'**	• Combine separate parts o Apply brake and emergency brake ▪ 1 mechanism and user activity • Combine user activities o Place and secure golf bag ▪ Automatic straps ▪ Flexible brackets that fit to shape of bag
<u>Directly Transfer Components</u>	• Golf bag securing mechanism

Table 11: Continued

<table>
<tr>
<td><u>Parameter Change</u></td>
<td>
• Materials
    o Aluminum frame
    o Lightweight chromoly steel frame
    o Carbon fiber brackets, accessories
    o Aluminum wheels
• Decrease scale
    o Frame thickness and diameter
    o Wheels and tires
    o Supporting brackets
    o Suspension and steering components
• Position
    o Wheel configuration
        ▪ 3 or 4 wheels
        ▪ 1 front tire
        ▪ 2 front tires
    o Golf bag- front, rear, side
    o Rider
        ▪ Standing
        ▪ Sitting
    o Steering
        ▪ Front
        ▪ Sides
    o Brakes
        ▪ Rear
        ▪ Front
</td>
</tr>
</table>

4.4 Final Concept

With the principles incorporated into the design process and ideas derived, the design continues with concept selection. The final design incorporates ideas in overall function and parts derived through applying the scaling principles. These ideas are taken from both sides of the scaling process, incorporating all ideas and design considerations into one final concept. First, an electric power source was chosen as the main means of power due to its advantages. This was chosen due to the customer likes from the electric push cart and golf cart. It will incorporate two-12 volt rechargeable batteries and a 24-volt electric motor. A renewable means of energy is also utilized through a solar panel that will lie on the deck of the cart. This solar panel will be constructed of tempered glass in order to sustain the weight of the rider. The solar panel will charge the batteries as the user is playing golf. The batteries, motor and electrical components will all be contained in the base of the cart. The batteries will remain in the base at all times, reducing user activities. Besides the solar panel for recharging, the cart will also contain an external plug to connect the cart to a common 15 amp/ 125 volt power socket.

The base of the cart will be composed of a steel frame with an outer aluminum shell to protect the internals. The frame will be constructed of 4130 chromoly steel tubing with a 0.75 inch diameter and 0.1 inch thickness. This frame idea was generated from the large scale golf cart which utilizes frame rails to support the body and components of the cart. The neck of the frame will contain a hinging point in order for the user to fold the front wheels and handle onto the base of the cart, reducing its overall area. This folding mechanism will utilize an automatic locking pin that will activate once in the correct position. When folding, the handle unit will fold down onto the deck where a lock will hold it in place for ease of transport. These were taken from the unfolding and folding method ideas of the manual and electric push carts. This keeps the number of user activities minimal, reducing setup time. Another accessory for the base of the cart is a slot in which a removable seat can be placed, also derived from the push carts. This seat will be adjustable in height to suit the user's comfort. It incorporates a locking clamp similar to that found on bicycle seat posts to secure it at the proper rider position.

The overall layout of the cart will be a three-wheel design with two larger wheels in front and one smaller wheel centered in the rear, as seen in Figure 36. The two front wheels are 10 inches in diameter while the rear wheel will be 6 inches. The reason why this configuration was chosen was due to its stability. With two wheels in front, there is no concern of tipping over when turning. This is common with three wheel vehicles that utilize one front wheel.

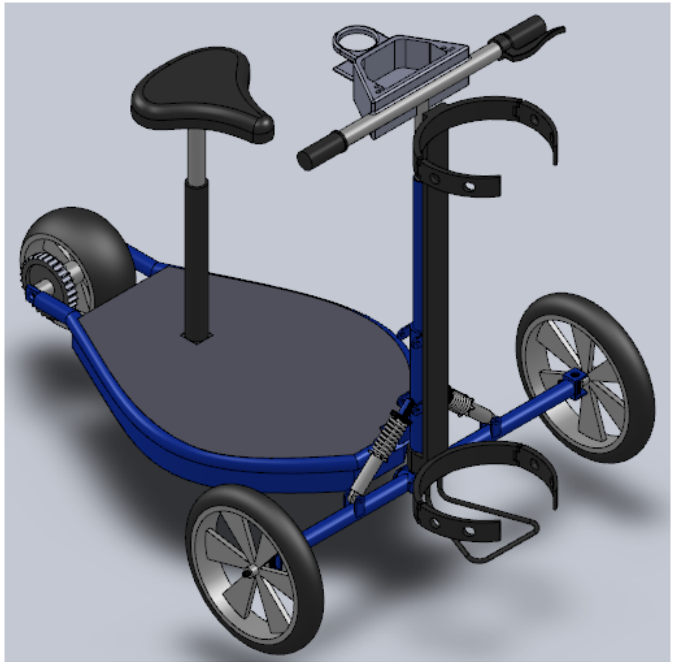


Figure 36: Final design rendering incorporating all ideas generated by applying the scaling principles

The electric motor will power the rear wheel through a belt drive system, connecting the motor to a pulley located on the rear axle. In case the batteries run out of power, this pulley can be slid out of line with the motor allowing the rear wheel to spin freely. This is another idea transferred from the electric push carts ability to disconnect its wheels from the motor. The rear axle will be bolted directly to the frame and spin smoothly by incorporating ball bearings on either side of the axle. The axle will also incorporate a single disc rotor that is utilized in the disc brake mechanism. The reason for choosing a rear-wheel setup is due to the added traction. It also aids in pushing the load instead of pulling which adds to its traction abilities. The rear disc brake was chosen instead of a front setup in order to maintain breaking balance. If placed in front of the cart, possible injuries could occur due to the cart flipping over from sudden stops.

The rear wheel will not contain any type of suspension components. This is due to keeping the weight of the cart light. The rear tire will be able to absorb small bumps. The front suspension will absorb the majority of the bumps. A swing axle suspension will be used which includes control arms, spindles and coilovers. With this type of suspension, each wheel can move independently of one another adding to the comfort level for the rider. Each control arm will be able to hinge due to a removable pin located at the upper mounting point of the coilover. Once disconnected, the coilover and arm can hinge upward again reducing its overall width. The control arms can then be locked into the folding position by replacing the pin in the upper mounting position. Figure 37 depicts the cart once folded at the neck and control arm hinges. The steering mechanism used will be a simple go-kart style setup. This design incorporates tie rods which are directly connected to the spindles and lower steering column. As the user rotates the handle, the steering column also rotates moving the tie rods and the spindles. These suspension and steering ideas were derived from the large scale golf cart since the push carts do not utilize steering and suspension. The folding capabilities were derived from the small scale push carts. It proved valuable in designing a suitable front suspension and steering system.

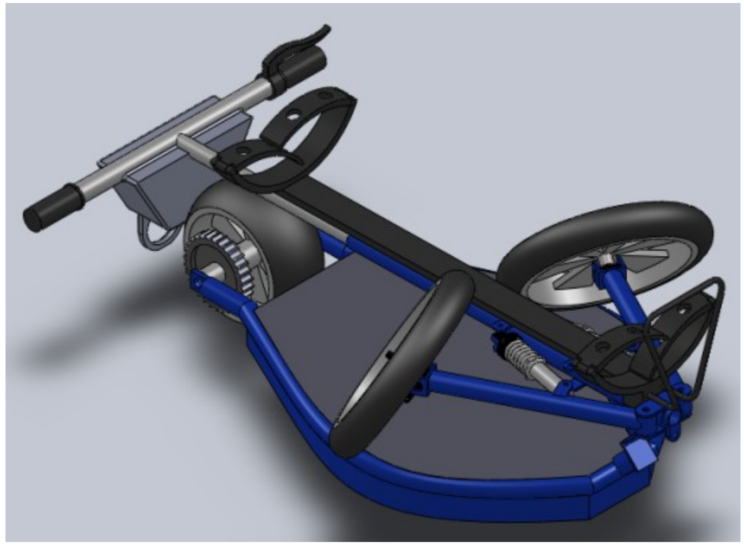


Figure 37: Ability of cart to fold to a compact size due to folding control arms and handle and removable seat

The steering column will be attached to the frame neck through two ball bearing rings and a locking nut. This type of setup is found in scooters and bicycles on the market today. A feature involved with the steering handle is a telescopic handle similar to that of the adjustable seat. The tightening clamp used on the seat will also be utilized for this feature. An accessory console will also be incorporated into the final design of the cart. It is located on top of the steering handle next to the users' hands. It features a small compartment that can fit small accessories such as keys, cell phone and other extras. This compartment will be covered by a hinging plastic lid that contains a clip to hold the user's score card. The console also contains a slot to hold extra golf balls, holes for golf tees and a cup holder. These console ideas were obtained from observing multiple push carts and choosing features from certain designs. A set of straight handlebars will be used for the final design. Both sides of the bars will include rubber grips for added comfort. The right side will also contain a twist throttle control incorporated into the grip. The left side will support the brake lever which will also incorporate the emergency brake. This will be activated when the hand brake is fully depressed and deactivate when pressed again.

The golf bag will be supported by the frame neck and handle in front of the cart. The reason this placement was chosen was due to the existing column support. No added brace or structure will need to be added, minimizing weight. The bag will also be centered in the middle of the cart resulting in proper balance. The golf bag will remain secured onto the cart through the use of adjustable plastic clamps. These clamps will be adjusted by the user to fit the diameter of the bag only one time. Once properly adjusted, the bag will simply slide into place and be securely held. The design was also chosen from observing push carts and their bag securing mechanisms. All ideas incorporated from the scaling principles are summarized in Figure 38 below. From the large scale, the drive-train and all its components were integrated into the final concept design. Small scale features include all folding and golf bag securing mechanisms as well as accessories.

Figure 38: Ideas generated and incorporated from large and small principle application

4.5 Senior Design Concept and Scaling Concept Comparison

By following the redesign process and applying the scaling principles to the scaling products, additions and differences are apparent when comparing the two final designs.

These scaling principles have a positive impact on the overall performance of the design, improving on the senior designs' concept. The scaling principles allowed for a more detailed insight into the individual mechanisms and features. The design teams' concept is shown below in Figure 39.

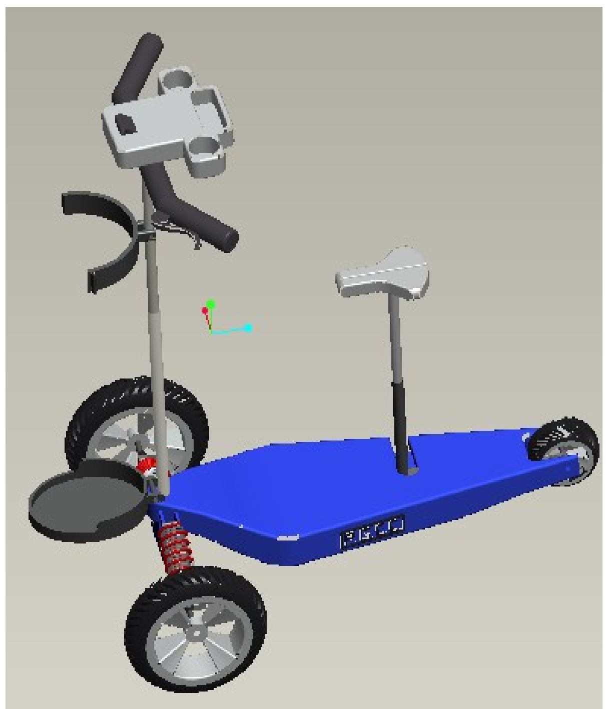


Figure 39: Senior design team concept

The principles focused attention into understanding and utilizing example products as a means of idea generation. This is clearly seen with the folding feature integrated into the cart. The senior design team only incorporated one folding mechanism into their design.

This was located on the steering column to allow only the handle to fold down. It did not include the folding of the control arms, minimizing the width of the cart. The team did not fully comprehend that the front suspension width is an important factor to consider within the customers' need. The automatic locking and handle locking features are other mechanism integrated into this final concept which reduces user activity.

Another aspect differentiating the two designs relates to the golf bag securing system. The team chose to use Velcro straps that must be adjusted constantly whereas this design incorporates brackets that are only adjusted once. This minimizes the number of user activities performed when in use. Such an idea was not realized by the senior design team due to the lack of understanding the user activities. The next difference lies with the braking mechanism. The team did not utilize an emergency brake on their design to keep the cart from moving when not in use. This is important since golf courses typically integrate elevation changes and without one, the cart could possibly roll off without the user. The new design uses a one step emergency brake that is incorporated into the hand brake.

Next, the solar panel idea integrated into the new design is another important difference. Because the senior design team did not search for all possible energy sources, they had limited choices to choose from. The scaling principles in conjunction with the energy source checklist allows for a wider array of possibilities. This solar panel could allow the user to play up to 36 holes on one charge, extending the battery life.

The last major difference between the two designs is the ability to disengage the rear axle from the motor. This idea was obtained from studying the electric push carts. Several customer reviews stated that they liked this feature since pushing the cart while still engaged was much more difficult. Without searching these products and reviews, this important idea would not have been realized. A summary of all differences between the two designs is depicted in Figure 40.

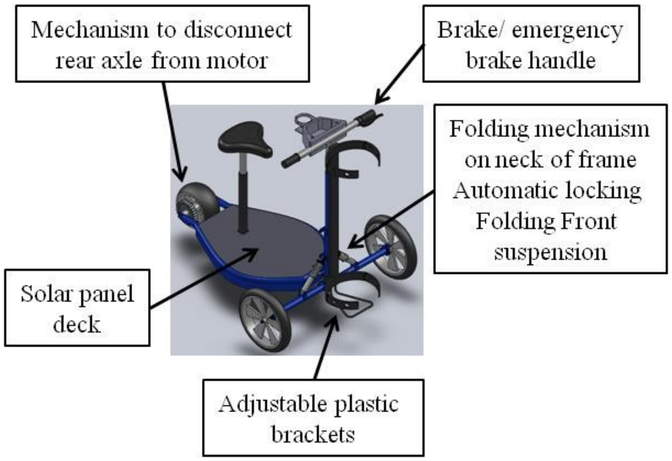
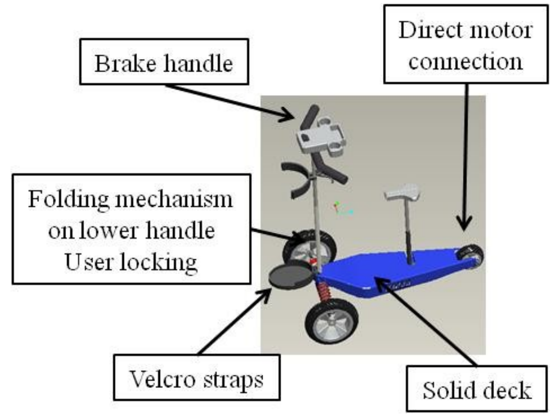
Scaling Process	Advantage of Scaling	Typical Process
	• **Motor disconnect:** Allows for user to push cart in case batteries discharge • **Brake/ emergency handle:** Allows cart to stay in place for added safety • **Folding mechanism:** Allows the cart to fold into a more compact size • **Solar panel:** Allows the batteries to charge when in use, longer battery life • **Adjustable brackets:** Minimizes user activity by only having to adjust once	

Figure 40: Differences between the senior design team final concept using a typical design process and the scaling process utilizing the scaling principles

Even though the layout of both designs is similar, the scaling method led to additional ideas that are very beneficial to the overall concept. The scaling principles focus on the customer needs and ways to accommodate these needs. They are met with higher standards due to an increase in their consideration. This is done through observing and studying example products in great detail in order to gain specific as well as broad ideas. The customer reviews are an additional aid in understanding there likes and dislikes for specific products. Due to this, small additions are added to the design that has a large effect on the overall performance. The additional folding feature and the new placement of the handle hinge help decrease the carts folded dimensions. This compact size will allow it to fit in smaller vehicles, increasing the market size. The automatic locking pins also remove user activities to make setup quicker and easier. These changes are an improvement over the senior design teams' concept due to the scaling method and principles.

5. CONCLUSIONS AND FUTURE WORK

Scaling of existing products and natural systems are continuously performed by engineers and designers. They are altered due to the changing needs and wants of customers, bioinspiration and design-by-analogy. Normally, engineers utilize a typical design or redesign process in which example products are reverse engineered. This is characteristically performed when designing a product that suits the same scale as the example product. When a product is designed to suit a different product scale, the redesign process falls short in guiding the designers through the scaling process. There is no current systematic approach to scaling products to the desired level. This research utilized an empirical research approach for understanding scaled products in order to generate a systematic process.

Due to the small amount of example products and/or systems used to derive these scaling principles, 46, not all possible changes that occur through the scaling process could be revealed. However, enough information was offered to derive six general scaling principles that form a bases on which ideas can be generated for product scaling. These principles include: ‘change energy source’, ‘simplify system’, ‘change method’, ‘combine functions’, ‘directly transfer components’ and ‘parameter change’. They all work together to break down the scaling product to its most basic foundations in order to generate novel and robust ideas. In conjunction with the change energy source principle, human and automatic energy checklists were derived. They proved valuable in understanding various combinations of power sources that can be implemented into a design. Depending on the design constraints and customer needs, the most fitting power source or combination of can be chosen from these checklists.

In order for these principles to be properly applied to the design problem and generate the most ideas, a scaling process is required. These steps and tasks include determining the scaling products' main function, sub-functions, user and machine activities, detailed mechanisms, parts and how they work in conjunction with one another. Customer analysis is another important step, which involves researching and gathering information on customer needs, wants, likes and dislikes. This contributes to appealing to the customer and in turn, develops a well-designed product that fulfills the preferred market scale. This scaling method in combination with the principles can be used to make the product development process more efficient as well as improve on the original design.

The comparative case study implemented in this research validated the process and principles as a possible idea generation method for product scaling. By taking on a previously solved design problem, designing a portable golf transportation system to transport the user and golf bag, the final concepts were compared to reveal the affects of the scaling principles on the final design. By using the scaling process in conjunction with the principles, there was greater insight into the products' individual functions and components. The principles require the scaling products to be broken down to their most basic functions in order to take full advantage of. This allows for more ideas to be generated for specific functions and sub-functions which in turn generated a better performing solution.

Even though the case study showed that ideas could be generated through the application of the scaling principles, there are some conclusions that cannot be made. First, it does not prove that they will work on a design problem which requires a large scale change. An example of this is scaling the original product or system at a macro scale to a nano scale. Secondly, the case study does not establish the principles as a biomimetic idea generation method. The design problem consisted of redesigning and scaling a market product, not a natural system. This can be solved by undertaking another case study which incorporates a biomimetic design problem. This can possibly show that these scaling principles can also work for bioinspiration.

The final concept incorporated features and ideas generated from both sides of the product scale. By scaling from two sides, a full understanding of important features was realized that are necessary to incorporate into the design. From the small scale products, compact features were the most important aspects considered. This includes all folding and locking mechanisms, golf bag securing mechanisms and user accessories. These small features appeal to the user and their activities, which are minimal in scale but make a big difference to the overall design. These features would not have been realized without the customer analysis including the customer reviews. From the large product scale, the entire drive-train portion of the design was comprehended. Due to the small scale products not containing much on this characteristic, another scale needed to be studied, the large scale product. From here, ideas were generated regarding possible motor, steering, suspension and frame configurations. This drive-train is important due to the fact that it must carry and propel both the golf bag and user throughout the golf course safely and consistently. The final design must fulfill the customer needs and design constraints which are what was accomplished through utilizing the scaling method and principles.

For this case study, extra input was also gathered on customer likes and dislikes which could have had an effect on the outcome of the final design when compared to the senior design concept. This was due to the redesign process and its utilization of determining customer likes and dislikes for the example product. The senior design teams' customer needs, likes and dislikes were based on their surveys. Even though this data was utilized for this study, the additional information could have altered the overall design process. Additional differences between the senior design team and this study include the amount of time spent on the design problem. First, the senior design team consisted of 3 students who evenly separated the design tasks. Next, two semesters were devoted to the design problem. The first semester incorporated project selection, market/ literature search, design methodology, concept designs and necessary analysis. The second semester continued with additional idea generation through the building of the physical prototype. In this study, only the author performed the necessary tasks required to solve the design problem. The amount of time spent on the design problem in this study was only 3 months. These various differences also have an effect on the final designs developed.

For future work on this scaling process and method, some recommendations are proposed from insights gained from this thesis. The background research, results and case study led to the following recommendations:

• Test the scaling process and principles: In order to increase the validation of this scaling process and principles as a viable idea generation method, an experiment can be implemented on a sample group of students. The experiment will include a problem statement, similar to this case study, on which to build from. One possible experiment can test the differences in ideas generated between a typical design process and the scaling process with its scaling principles. First, the group will go through the typical design process and steps in order to generate as many ideas possible in a given amount of time. Next, the group will follow the scaling process and generate as many ideas as possible in that same amount of time. The number of ideas generated from the two processes can then be compared to see if the scaling process aided in determining more ideas. Another possible experiment is testing whether scaling from two product scales is better than scaling from just one. The experiment will consist of two groups which both have all necessary information and steps provided to them. The first group will follow the scaling process and generate as many ideas possible from applying the principles to only one scale, small. The second group will be given additional information on the other scale on which they can apply to both scales to generate as many ideas as possible. Once completed, the number of generated ideas can be compared to determine whether scaling from two scales is better than one. All information gathered will be analyzed to determine the effectiveness of this process and principles.

• Study and research a greater number of example products: The amount of example products researched for determining these scaling principles can be increased in order to view a broader range of items. This increase in products might uncover additional insights into product differences throughout the product scale. This can include increasing the number of product categories as well as product scales within each category. Increasing the number of product categories widens the amount of products studied and the ability to view additional mechanisms and features not covered within this thesis. The number of product scales within each product category can also be increased to view additional differences. In this thesis, the number of product scales for each category was two or three; this included small, medium and large. This number can be increased to five or six which will give a more detailed view into the more subtle changes made when the scale change is not very dramatic. This will allow for more detailed sub-principles to be derived.

• Compare to additional idea generation methods: To test its effectiveness as an idea generation method, an experiment can be made to compare it to other common methods. This experiment will consist of comparing the number of ideas generated from utilizing one method, say TIPS/TRIZ, to the scaling method. It will again entail a design problem and all necessary information required to properly apply both methods. The group will first generate ideas using the TIPS/TRIZ method in a given amount of time. Then using the scaling method, generate as many ideas in the same amount of time. The results can then be compared to determine whether the scaling method derived more ideas. This can also be compared to other idea generation methods, such as the Wordtree method and 6-3-5.

• Apply to another case study: This process and principles were only applied to one case study in which ideas were generated and problem solved. It was then compared to a previous design which was undertaken and solved at an earlier date to view the differences between the final concepts. The results showed that by utilizing the scaling principles, a more detailed understanding of the product and its features was realized. Another case study can be undertaken to determine whether the same results are derived. It can entail applying the scaling method and principles to another previously solved design problem to view their differences. The comparison between the results of the two case studies can show how the principles affect the idea generation process. Additional case studies can also be performed on various product categories and scales. This will prove that the principles work on all product scales and categories, not just this one.

REFERENCES

123rf. Circular saw blade. Photo. <http://www.123rf.com/photo_9111306_circular-saw-blade-for-wood-isolated-on-white.html>. Accessed: 25 Aug. 2010.

Adventuresincapitalism. Bread making factory. Photo. <http://adventuresincapitalism.com/post/2010/09/06/Mongolia-Part-II-(Company-Visits).aspx>. Accessed: 24 Aug. 2010

Aircompressorhut. Air compressor. Photo. <http://aircompressorhut.info/>. Accessed: 24 Aug. 2010.

Altshuller, G. (1999). *The Innovation Algorithm: TRIZ, Systematic Innovation and Technical Creativity*, Worchester, MA: Technical Innovation Center.

Amazon. Tape measure. Photo. <http://www.amazon.com/Stanley-33-725-25-Foot-FatMax-Measure/dp/B00002PV66>. Accessed: 24 Aug. 2010.

Bagboycompany. Bag boy automatic folding push cart. Photo. <http://www.bagboycompany.com/tc.aspx?top=innovation&i=img_innov>. Accessed: 2 Feb. 2011.

Bandsawcutting. Bandsaw. Photo. <http://www.bandsawcutting.com/2011/02/07/tile-band-saw/>. Accessed: 24 Aug. 2010.

Batterysource. Ezgo TXT golf cart. Photo. <http://www.batterysource.com/page.cfm/Golf%20Car%20Show%20Room/TXT.html>. Accessed: 3 Feb. 2011.

Biodiesel-machine. Nut sheller. Photo. <http://www.biodiesel-machine.com/peanut-sheller.html>. Accessed: 22 Aug. 2010.

Blogs.riverfronttimes. Wheelbarrow. Photo. <http://blogs.riverfronttimes.com/therundown/2008/12/last_minute_gifts_for_chris_duncan_richie_incognito_jim_haslett_albert_pujols_gary_pinkel_rick_majerus.php>. Accessed: 25 Aug. 2010.

Bogatyrev, N., and Bogatyreva, O. (2009). TRIZ evolution trends in biological and technological design strategies. *Proceedings of the 19th CIRP Design Conference-Competitive Design*. Cranfield University, 30-31March 2009. 293-299.

Brain, M., (2001). *How Stuff Works*, New York, Hungry Minds.

Bridgman, P.W., (1922). *Dimensional Analysis*. New Haven CT, Yale University Press.

Budologyproductions. Earth mover. Photo. <http://www.budologyproductions.com/?p=54>. Accessed: 25 Aug. 2010.

Bushnell, D. (2005). Scaling: Wind tunnel to flight. *Annual Review of Fluid Mechanics*, *38 (1),* 111-128.

Carpinteri, A., Cornetti, P., and Puzzi, S. (2006). Scaling laws and multiscale approach in the mechanics of heterogeneous and disordered materials. *Applied Mechanics Reviews*, *59*, 283-305.

Cartaholics.com. <http://cartaholics.com>. Accessed: 2 Feb. 2011

Chemistry-Dictionary. Extensive Property, http://www.chemistry-dictionary.com/definition/extensive+property.php, 2011. Accessed: 1 Feb. 2011.

Cheong, M. S., Cho, D. W., and Ehmann, K. F. (1999). Identification and control for micro-drilling productivity enhancement. *International Journal of Machine Tools and Manufacture* 39 (10), 1539-1561.

Clingclimbing. Magnetic climbing system. Photo. <http://www.clingclimbing.com>. Accessed: 20 Jan. 2011.

Crankyfarmer. Crossbow. Photo. <http://www.crankyfarmer.com/netcrossbow.html>. Accessed: 25 Aug. 2010.

Critical Golf. < http://criticalgolf.com/golf-cart-reviews/>. Accessed: 2 Feb. 2011.

Denkba , E., and Vaseashta, A. (2008). Nanotechnology in medicine and health sciences. *NANO: Brief Reports and Reviews 3 (4),* 263-269.

Dictionary A, Concurrent, in *Dictionary.com Unabridged*. http://dictionary.reference.com. Accessed: 10 Feb. 2011.

Dictionary B, Physical Property, in *WordNet® 3.0*. http://dictionary.reference.com. Accessed: 10 Feb. 2011.

Durhamcountync. Water treatment plant. Photo. <http://www.durhamcountync.gov/departments/ceng/Wastewater_Treatmen.html>. Accessed: 24 Aug. 2010.

Ebay. <http://www.ebay.com>. Accessed: 22 Aug. 2010.

Ez Go. <http://www.ezgo.com>. Accessed: 2 Feb. 2011.

Ezgogolfcart. Ezgo rear axle electric. Photo. <http://ezgolfcart.com/i-5921836-rear-axle-assm-complete-w-diff-e-z-go-txt-94-up.html>. Accessed: 3 Feb. 2011.

Faqs. Nut cracker. Photo. <http://www.faqs.org/photo-dict/phrase/1248/nutcracker.html>. Accessed: 22 Aug. 2010.

Fish, F., and Lauder, G. (2005). Passive and active flow control by swimming fishes and mammals. *Annual Review of Fluid Mechanics*, *38 (1),* 193-224.

Flickr. Bicycle. Photo. <http://www.flickr.com/photos/dbchq/sets/72157623066873185/detail/>. Accessed: 25 Aug. 2010

Galilei, G. (1638). *Two New Sciences*, Translated by Henry Crew and Alfonso de Salvio (Dover, New York, 1954). Originally published by Elzevir.

Geekalerts. Shaking flashlight. Photo. <http://www.geekalerts.com/shaker-flashlight/>. Accessed: 25 Aug. 2010.

Golfcartcomparison. <http://golfcartcomparison.com>. Accessed: 2 Feb. 2011.

Golfsmith. <http://www.golfsmith.com>. Accessed: 2 Feb. 2011.

Golfsmith. Clicgear Model 3.0. Photo. <http://www.golfsmith.com/products/304893/Clicgear/Model_3.0>. Accessed: 2 Feb. 2011.

Golfsmith. Tour trek tahoecart. Photo. <http://www.golfsmith.com/products/299110/Tour_Trek/Tahoe_Push_Cart>. Accessed: 2 Feb. 2011.

Google. <http://googe.com>. Accessed: 20 Aug. 2010.

Homeconstructionshop. Hand saw close up. Photo. <http://homeconstructionshop.com/hand-tools/the-hand-saw-is-it-a-cross-cut-saw-or-a-rip-saw>. Accessed: 24 Aug. 2010.

Homeinteriorszone. Home bread maker. Photo. <http://www.homeinteriorszone.com/home-appliances/top-3-bread-making-machines-2011/>. Accessed: 24 Aug. 2010.

Howstuffworks. <http://www.howstuffworks.com>. Accessed: 26 Aug. 2010.

Hsu, T.-R. (2002). Miniaturization- A Paradigm Shift in Advanced Manufacturing and Education. *IEEE/ASME International Conference on Advanced Manufacturing Technologies and Education in the 21st Century*. Chia-Yi, Taiwan, Republic of China. 10-15 August 2002.

Institute, T. B. (2008). What Is Biomimicry?, http://asknature.org/article/view/what_is_biomimicry. Accessed: 1/21/2011.

Ipsen, D.C. (1960). *Units, Dimensions, and Dimensionless Numbers.* New York, McGraw-Hill Book Company, Inc.

Jiao, J., Simpson, T. W., and Siddique, Z. (2007). Product family design and platform-based product development: A state-of-the-art review. *Journal of Intelligent Manufacturing*, *18 (1),* pp. 5-29.

Korchagin, O., Novikov, V., Rakov, E., Kuznetsov, V., and Tarasevich, M. (2009). Carbon nanotubes as efficient catalyst supports for fuel cells with direct ethanol oxidation, *Russian Journal of Electrochemistry 46 (8),* 882-889.

Langhaar, Henry L. (1951). *Dimensional Analysis and Theory of Models.* New York, John Wiley & Sons, Inc.

Leemfgco. Electric nut cracker. Photo. <http://www.leemfgco.com/store/index.php?act=viewProd&productId=7>. Accessed: 22 Aug. 2010.

Legacy.lclark. Gecko foot close up. Photo. <http://legacy.lclark.edu/>. Accessed: 15 Jan. 2011.

Library Tamu. <http://www.library.tamu.edu>. Accessed: 26 Aug. 2010.

Linsey, J.S. (2007). Design-By-Analogy and Representation in Innovative Engineering Concept Generation. Ph. D. The University of Texas at Austin.

Lohmann, A. (1989). Scaling laws for lens systems. *Applied Optics*, pp. 28 (23), 4996-4998.

Macaulay, D., Ardley, N., and Leonard, S. (1998). *The New Way Things Work,* Boston: Houghton Mifflin.

Malleast. Sun mountain micro cart. Photo. <http://www.malleast.com/new-2009-sun-mountain-micro-cart-golf-trolley-silver-p-1819.html>. Accessed: 2 Feb. 2011.

Martin, M. V., and Ishii, K. (2002). Design for variety: Developing standardized and modularized product platform architectures. *Research in engineering Design 13 (4)*, 213-235.

Meyer, M. H., and Utterback, J. M. (1992). The Product Family and the Dynamics of Core Capability. International Center for Research on the Management of Technology, Sloan School of Management, Massachusetts Institute of Technology.

Nosonovsky, M. and Bhushan, B. (2005). Roughness optimization for biomimetic superhydrophobic surfaces. *Microsystem Technologies 11 (7),* 535-549.

Ocmonstercarts. Golf cart brake/ parking brake pedal. Photo. <http://ocmonstercarts.com/cart/products/41/index.php>. Accessed: 5 Feb. 2011.

Openlearn.open A. Goose grass hooks close up. Photo. <http://openlearn.open.ac.uk/mod/oucontent/view.php?id=397861&section=1.11.5>. Accessed: 20 Jan. 2011.

Openlearn.open B. Velcro close up. Photo. <http://openlearn.open.ac.uk/mod/oucontent/view.php?id=397861&section=1.11.5>. Accessed: 20 Jan. 2011.

Oshiro, R.E. and Alves, M. (2009). Scaling of structures subject to impact loads when using a power law constitutive equation. *International Journal of Solids and Structures*, *46*, 3412-3421.

Otto, K., Wood, K. (2001). *Product Design Techniques in Reverse Engineering and New Product Development*. Upper Saddle River, NJ, Prentice Hall.

Pack, R. T., Christopher Jr, J. L., and Kawamura, K. (1997). A rubbertuator-based structure-climbing inspection robot, *Proceedings of the 1997 IEEE Conference on Robotics and Automation,*Albuquerque, NM., 1869-1874.

Paula, G. (1997). Reinventing a core product line. *Mechanical Engineering 119 (10),* 102-103.

Peterson, H. (1984). Scaling laws applied to wind turbine design. *Wind Engineering 8 (2),* 99-108.

Peterson, M. (2002). Galileo's discovery of scaling laws. *American Journal of Physics 70*, 575-580.

Pugno, N. (2008). Spiderman gloves. *Nano Today 3 (5-6),* 35-41.

Rei. Water filter bag. Photo. <http://www.rei.com/product/778043/sawyer-water-filter-system-4-liter>. Accessed: 24 Aug. 2010.

Ren, L., Han, Z., Li, J., and Tong, J. (2002). Effects of non-smooth characteristics on bionic bulldozer blades in resistance reduction against soil. *Journal of Terramechanics*, *39 (4),* pp. 221-230.

Reviewsalert. Coleman air pump. Photo. <http://reviewsalert.com/coleman-air-pump-large-dual-action-hand/>. Accessed: 24 Aug. 2010.

Samsomcnc. Plasma cutter cnc. Photo. <http://www.samsoncnc.com/art.php>. Accessed: 24 Aug. 2010.

Sand Trap, The. < http://thesandtrap.com/b/reviews>. Accessed: 2 Feb. 2011.

Sand Trap, The. Bag boy navigator electric cart. Photo. <http://thesandtrap.com/b/accessories/page/2>. Accessed: 2 Feb. 2011

Sand Trap, The. Sun mountain speed E cart. Photo. <http://thesandtrap.com/b/accessories/sun_mountain_speed_e_cart_review>. Accessed: 2 Feb. 2011.

Sanderson, S., and Uzumeri, M. (1995). Managing product families: The case of the sony walkman. *Research Policy* 24 (5), 761-782.

Saunders, M. N., Seepersad, C. C., and Hölttä-Otto, K. (2009). The characteristics of innovative, mechanical products. *Proceedings of the ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference,* 30 August – 2 September, San Diego, CA.

ScientificAmerican. Gecko foot. Photo. <http://www.scientificamerican.com/media/inline/>. Accessed: 15 Jan. 2011

Simpson, T., Siddique, Z., and Jiao, J. (2006). Platform-based product family development. *Product Platform and Product Family Design: Methods and Applications*. pp. 1–15. New York: Springer.

Simpson, T. W., Maier, J. R. A., and Mistree, F. (2001). Product platform design: Method and application. *Research in Engineering Design 13 (1),* pp. 2-22.

Singh, A., Yoon, E.S., Jackson, R. (2009). Biomimetics: The science of imitating nature. *Tribology & Lubrication Technology 65 (2),* 40-47.

Singh, V., Skiles, S. M., Krager, J. E., Wood, K. L., Jensen, D., and Sierakowski, R. (2009). Innovations in design through transformation: A fundamental study of transformation principles. *Journal of Mechanical Design* (131), 081010-1 – 081010-18.

Triantafyllou, M., Hover, F., Techet, A., and Yue, D. (2005). Review of hydrodynamic scaling laws in aquatic locomotion and fishlike swimming. *Applied Mechanics Reviews 58,* 226-237.

Vakili, V., and Shu, L. (2001). Towards Biomimetic Concept Generation. *Proceedings of ASME 2001 Design Engineering Technical Conference.* Pittsburgh, PA, 9-12 Sept., DETC2001/DTM-21715.

Wautelet, M. (2001). Scaling laws in the macro-, micro-and nanoworlds. *European Journal of Physics 22*, pp. 601.

Williamcameronwoodworking. Laser tape. Photo. <http://www.williamcameronwoodworking.com/Tools/tape_measures.htm>. Accessed: 24 Aug. 2010.

Yamanouchi, T. (1989). Breakthrough: The development of the canon personal copier. *Long Range Planning 22 (5),* 11-21.

Zacharias, N. A., and Yassine, A. A. (2008). Optimal platform investment for product family design. *Journal of Intelligent Manufacturing 19 (2),* 131-148.

APPENDIX A

DETAILED EXAMPLE PRODUCT CLASSES (How stuff works, 2010)

Building

- Frame
  - Small
    - Wood
  - Large
    - Metal
- Structure
  - Small
    - Random walls
  - Large
    - Large steel box, small boxes inside

Shelling machine – Efficiently crack and remove the outer shell of a nut without damaging the nut.

- Material feed
  - Nut cracker
    - Manual- Place 1 nut
  - Electric nut cracker
    - Manual- Place 1 nut
  - Electric shelling machine
    - Automatic- Conveyor
- Material separation
  - Small
    - Manual- hand powered cracking
  - Medium
    - Automatic- electric powered rotating mechanism
  - Large
    - Automatic- electric motor rotating mechanism
- Material extraction
  - Small
    - Manual- hand pick shell from nut
  - Medium
    - Manual- hand pick shells from nuts
  - Large
    - Automatic- various size screen sifting

Sewing- A means of attaching pieces of fabric together.

- Power
    - Small
        - Hand
    - Large
        - Electric motor
- Stitch
    - Small
        - Continuous thread
    - Large
        - Loop stitch
        - Multiple threads

Press- A way to act upon an object "with steadily applied weight or force". Dictionary.com

- Material feed
    - Mechanical vice
        - Manual- hand place object
    - Hydraulic press
        - Manual- hand place object
        - Automatic- robotic arms place object
- Action
    - Small
        - Manual- hand powered rotating mechanism
    - Large
        - Automatic- mechanical/ electric motor powered rotating mechanism
        - Hydraulic- pressurized fluid applies force
- Material extraction
    - Small
        - Manual- hand pick object
    - Large
        - Automatic- robotic pick object

Water filtration- Efficiently remove all harmful bacteria and unwanted organisms from unprocessed water to be able to drink.

- Water accumulation
    - Portable water filter
        - Manually
        - Pour
        - In water source
    - City water filtration plant
        - Automatically
        - Pumps

- Storage
    - Small
        - Small container
    - Large
        - Large tank
- Filtration method
    - Small
        - Screening
        - Ultraviolet light
        - Chemical(iodine, chlorine)
    - Large
        - Screening
        - Soda ash
        - Chlorine
        - Ph adjustment
        - Flocculation
        - Sedimentation
        - Sand/ lava filtration

Weight scale- A way to accurately determine the weight of an object.

- Weight calculation
    - Home weight scale
        - Mechanical springs
        - Rack and pinion gear
    - Truck weight scale
        - Automatic- electronic load cell calculation

Air pump- A way to force air into an object.

- Power
    - Hand pump
        - Manual- hand action
    - Air compressor
        - Automatic- electric pump
- Method
    - Small
        - Reciprocating
        - Piston
    - Large
        - Reciprocating
        - Rotary
        - Centrifugal
- Storage
    - Small

        - Direct air into object
        - No tank
        - One way valve
    - Large
        - Pressurized storage tank
        - No tank
        - One way valve

Saw- A device that can cut through an object.

- Power
    - Hand saw
        - Manual- hand operated
    - Chain/ circular saw
        - Automatic- electric/ gas motor
- Method
    - Small
        - Oscillation of arm
    - Large
        - Electric / gas motor rotates cutting chain
- Blade
    - Small
        - Serrated teeth
        - Thin solid body
    - Large
        - Serrated teeth
        - Thick rotating chain body
        - Thin rotating circular disk

Drill- A device that can cut a hole into an object.

- Power
    - Hand powered
        - Manual- hand operated
    - Portable drill
        - Automatic- electric motor
    - Oil well
        - Automatic- electric/ gas motor
- Method
    - Small
        - Rotation of hand
    - Medium
        - Electric motor rotates bit

    - Large
        - Gas motor rotates bit
- Bit
    - Small
        - Steel
    - Medium
        - High carbon steel
    - Large
        - High carbon steel
        - Titanium

Lock- A device for securing an object.

- Locking mechanism
    - Combination lock
        - Mechanical tumblers
    - Safe
        - Mechanical tumblers
        - Magnetic
        - Electronic

Length measure

- Length calculation
    - Ruler/ tape measure
        - Manual- visual comparison to markings
    - Electronic ruler
        - Automatic- Time it takes for laser to return to origin determines length

Watch- A device that calculates time.

- Time calculation
    - Hourglass
        - Calculated amount of sand through a hole
    - Mechanical watch
        - Automatic- gears measure seconds, minutes, and hours
        - Automatic- quartz crystal
    - Electronic watch
        - Automatic- electronic computer chip

Compactor- A means of compacting dirt by vibration/ pounding.

- Power

  - Hand stomper
    - Manual- hand
  - Motorized compactor
    - Automatic- gasoline motor
  - Crane compactor
    - Automatic- gasoline motor
- Method
  - Small
    - Arm lifting and dropping
  - Medium
    - Motor drives rotating arm which moves compactor up and down
  - Large
    - Motor lifts large weight through cables up and down

Trencher- A means of digging a narrow yet deep cut into the earth.

- Power
  - Plow
    - Manual- hand
  - Trencher
    - Automatic-gasoline motor
- Method
  - Small
    - Pull plow through dirt
    - Animal pulls plow through dirt
  - Large
    - Motor drives rotating chain which cuts through dirt
- Blade
  - Small
    - Large steel plow
  - Large
    - Large rotating serrated chain

Dirt removal- A means of removing dirt.

- Power
  - Shovel
    - Manual- hand
  - Back hoe
    - Automatic-gasoline motor
- Method
  - Small
    - Dig shovel into ground to remove dirt
  - Large

        - Motor drives hydraulic pistons which digs shovel into ground to remove dirt
- Blade
    - Small
        - Small steel shovel
    - Large
        - Large steel bucket with teeth

Earth mover- A means of moving dirt.

- Power
    - Wheelbarrow
        - Manual- hand
    - Dump truck
        - Automatic-gasoline motor
- Method
    - Small
        - Person pushes mall bucket with wheels
    - Large
        - Motor drives large truck with huge bucket
        - Motor drives hydraulic pistons which lift one side of bucket to remove dirt
- Bucket
    - Small
        - Small steel dish
    - Large
        - Large steel truck bed

Grain harvesting- Means of gathering and preparing grain for sale

- Power
    - Scythe
        - Manual- hand
    - Combine harvester
        - Automatic-gasoline motor
- Method
    - Small
        - Swing scythe through grain stalks to cut
        - Gather grain stalks into sheaves and tie into bunches
        - Thresh grain by separating cereal grain from chaff
    - Large
        - Motor drives rotating mechanism which cuts stalks
        - Motor drives auger which feeds grain into elevator

        - Mechanical elevator carries grain to threshing drum
        - Motor drives threshing drum which separates cereal from chaff
- Blade
    - Small
        - Long thin steel blade
    - Large
        - Large rotating metal blades

Cotton picking- Means of picking cotton and seed from plant to use for textiles

- Power
    - Hand laborers
        - Manual- hand
    - Cotton picker
        - Automatic-gasoline motor
- Method
    - Small
        - Pick cotton lint and seed from stalks by hand
        - Gather cotton into large containers for travel
    - Large
        - Motor drives rotating rows of barbed spindles which remove seed-cotton
        - Motor drives rotating mechanism opposite direction to remove seed-cotton

Field cultivator- farm implement for stirring and pulverizing the soil, either before planting or to remove weeds and to aerate and loosen the soil after the crop has begun to grow.

- Power
    - Hand cultivator
        - Manual- hand
    - Field cultivator/ tiller
        - Automatic-gasoline motor
- Method
    - Small
        - Dig into soil to loosen
    - Large
        - Motor drives rotating auger
- Tool
    - Small
        - Small steel pronged tool
    - Large

        - Large steel auger

Bread maker- A means of making bread.

- Power
    - Hand
        - Manual- hand
    - Home bread maker
        - Automatic- electric motor
    - Industry bread maker
        - Automatic- electric motor
- Mixing
    - Small
        - Hand
    - Large
        - Rotating metal arms
    - Larger
        - Rotating metal arms
- Container
    - Small
        - Small bowl
    - Large
        - Medium bowl/ tub
        - Use as oven
    - Larger
        - Large tub
- Baking
    - Small
        - Home oven
    - Large
        - Heating plate/ oven
    - Larger
        - Industrial oven

Blender/ mixer- A means of mixing together various substances.

- Power
    - Whisk
        - Manual- hand
    - Hand mixer
        - Automatic- electric motor
    - Industrial mixer
        - Automatic- electric motor
- Method
    - Small

        - Arm moves whisk rapidly through substance
    - Medium
        - Motor rapidly rotates small steel blades
    - Large
        - Motor rapidly rotates large steel blades

Oven

Coffee grinder- A means of grinding coffee.

- Power
    - Hand operated
        - Manual- hand
    - Home grinder
        - Automatic- electric motor
    - Industry grinder
        - Automatic- electric motor
- Method
    - Small
        - Arm rotates stone against another stone
    - Medium
        - Motor rotates metal blades
    - Large
        - Motor rotates metal blades

Potato peeler- A means of peeling potatoes.

- Power
    - Hand peeler
        - Manual- hand
    - Industrial peeler
        - Automatic- electric motor
- Method
    - Small
        - Arm moves sharp blade over potato
    - Large
        - Motor rotates steel tumbler

Juicer- A means of juicing various fruits and vegetables.

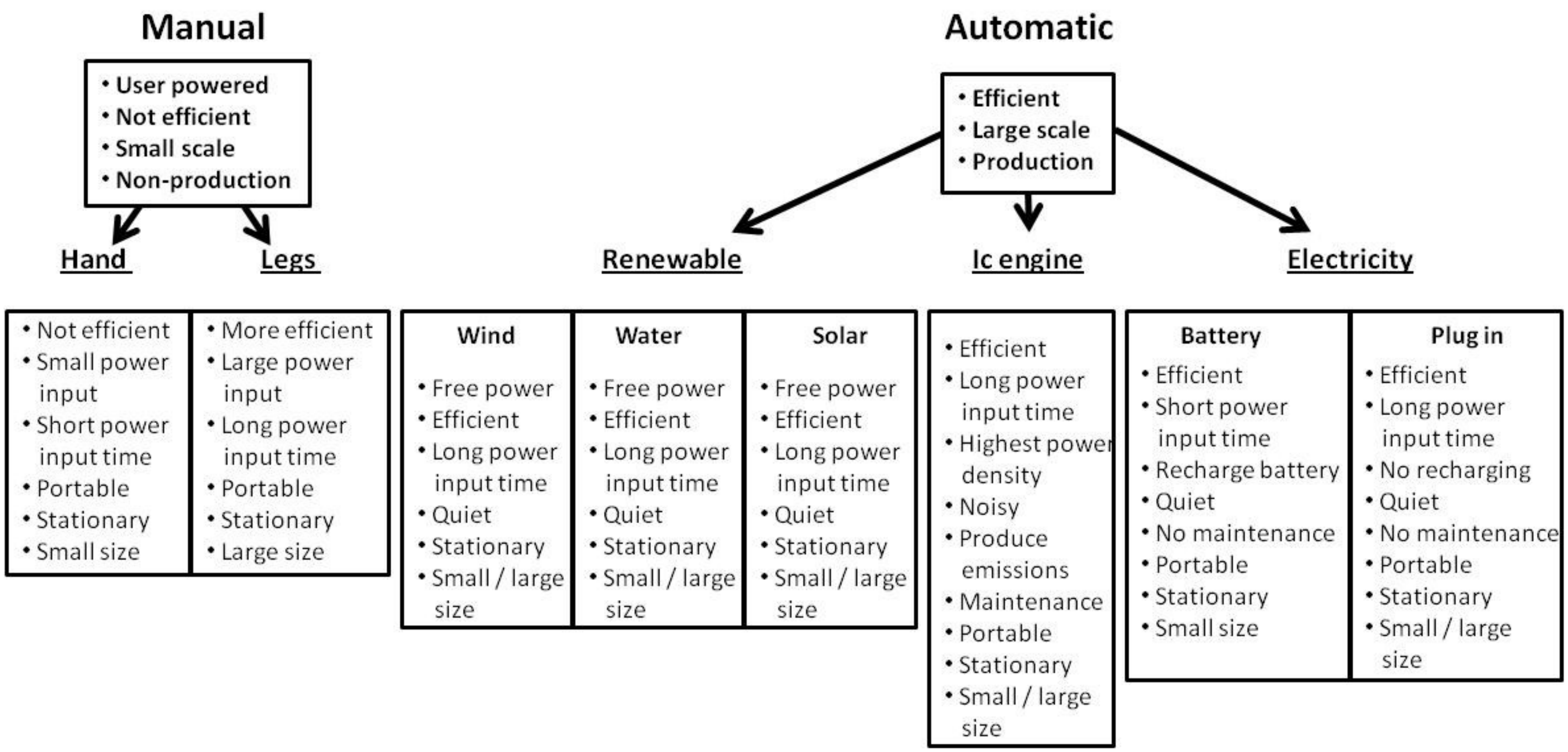
- Power
    - Hand
        - Manual- hand
    - Home juicer
        - Automatic- electric motor

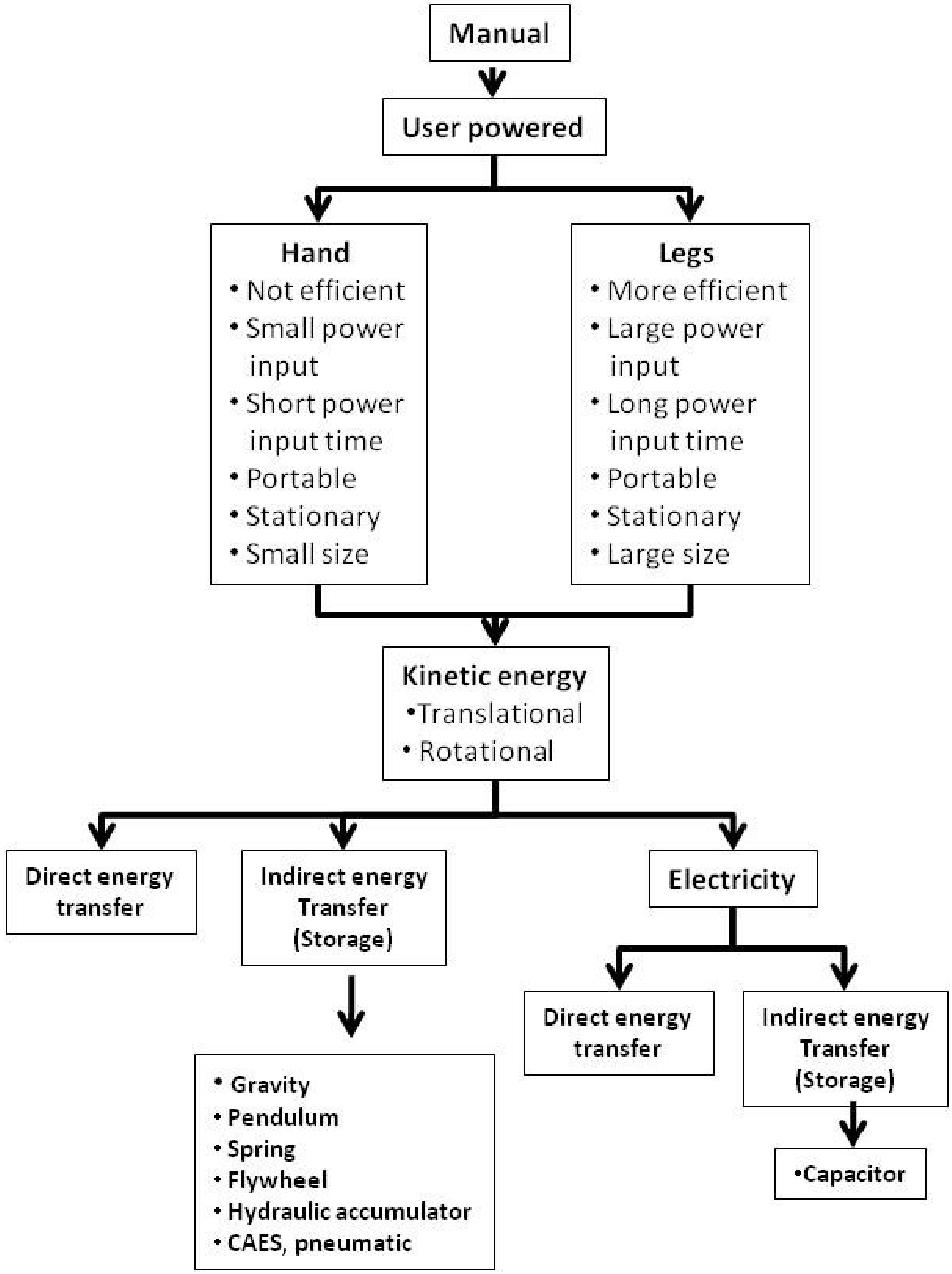
    - Industrial juicer
        - Automatic- electric motor
- Method
    - Small
        - Hand squeezes fruit
    - Medium
        - Motor rotates juicing head
    - Large
        - Motor rapidly rotates metal grinding wheel

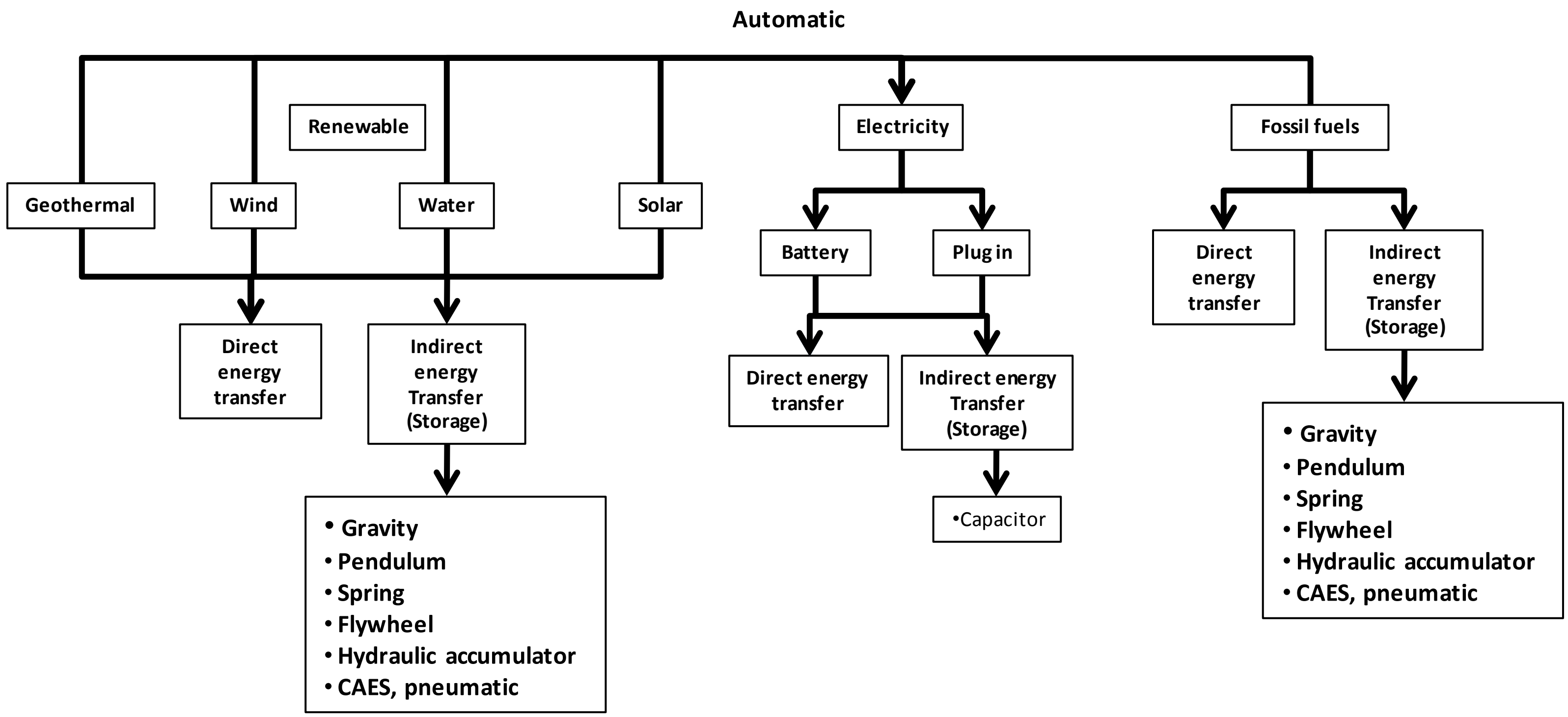
Energy generator- A means of generating energy.

- Power
    - Small
        - Manual- Hand
    - Large
        - Automatic
            - Gasoline motor
            - Water
            - Wind
- Method
    - Small
        - Rotate shaft which runs generator
    - Large
        - Motor/ water/ wind rotates shaft which runs generator

APPENDIX B
ENERGY SOURCE FIGURES




Manual
User powered
Hand
• Not efficient
• Small power input
• Short power input time
• Portable
• Stationary
• Small size
Legs
• More efficient
• Large power input
• Long power input time
• Portable
• Stationary
• Large size
Kinetic energy
•Translational
• Rotational
Direct energy transfer
Indirect energy Transfer (Storage)
• Gravity
• Pendulum
• Spring
• Flywheel
• Hydraulic accumulator
• CAES, pneumatic
Electricity
Direct energy transfer
Indirect energy Transfer (Storage)
•Capacitor


Automatic
Renewable
Electricity
Fossil fuels
Geothermal
Wind
Water
Solar
Battery
Plug in
Direct energy transfer
Indirect energy Transfer (Storage)
Direct energy transfer
Indirect energy Transfer (Storage)
Direct energy transfer
Indirect energy Transfer (Storage)
Direct energy transfer
Indirect energy Transfer (Storage)
• Gravity
• Pendulum
• Spring
• Flywheel
• Hydraulic accumulator
• CAES, pneumatic
•Capacitor
• Gravity
• Pendulum
• Spring
• Flywheel
• Hydraulic accumulator
• CAES, pneumatic

APPENDIX C

CASE STUDY SCALING PRODUCT DIFFERENCES (Golf Smith, 2011)

Small (walking stroller)

- Manually operated
- Human powered
- Plastic frame
- 3 legs/ wheels
- Handle
- Collapsible
- Foldable
- 5- 10 lbs
- Golf bag platform
- Golf bag strap
- Holder balls/ tees

Functions

- Transport and hold 1 golf bag
- Hold balls and tees

Medium (electric scooter)

- Automatic
- Electric motor
- 1 rechargeable batt.
- Throttle computer control
- Adjustable throttle
- Mech. Disc brake
- Belt driven
- Rear wheel drive
- 2 front wheels
- 2 front control arms
- 2 front shocks
- Adjustable steering linkage
- Rotating handle
- Folding handle
- Crommolly steel
- Aluminum diamond plate
- 60 lbs.
- Golf bag platform
- Golf bag strap
- Holder balls/ tees

Functions

- Transport and hold 1 golf bag

Large (golf cart)

- Automatic
- Electric motor
- 6 rechargeable batteries
- Throttle computer control
- Adjustable accelerator
- Mech. drum brake
- Parking brake
- Rear axle
- Rear wheel drive
- 2 front wheels
- Independent leaf suspension
- Hydraulic shocks
- Rack and pinion front steering
- Steering wheel
- Steel frame
- Fiberglass body
- Front cushion seat
- 500 lbs.
- Golf bag platform
- Golf bag straps

Functions

- Transport and hold 2 golf bag

APPENDIX D

TOUR TREK TAHOE CART PARTS LIST

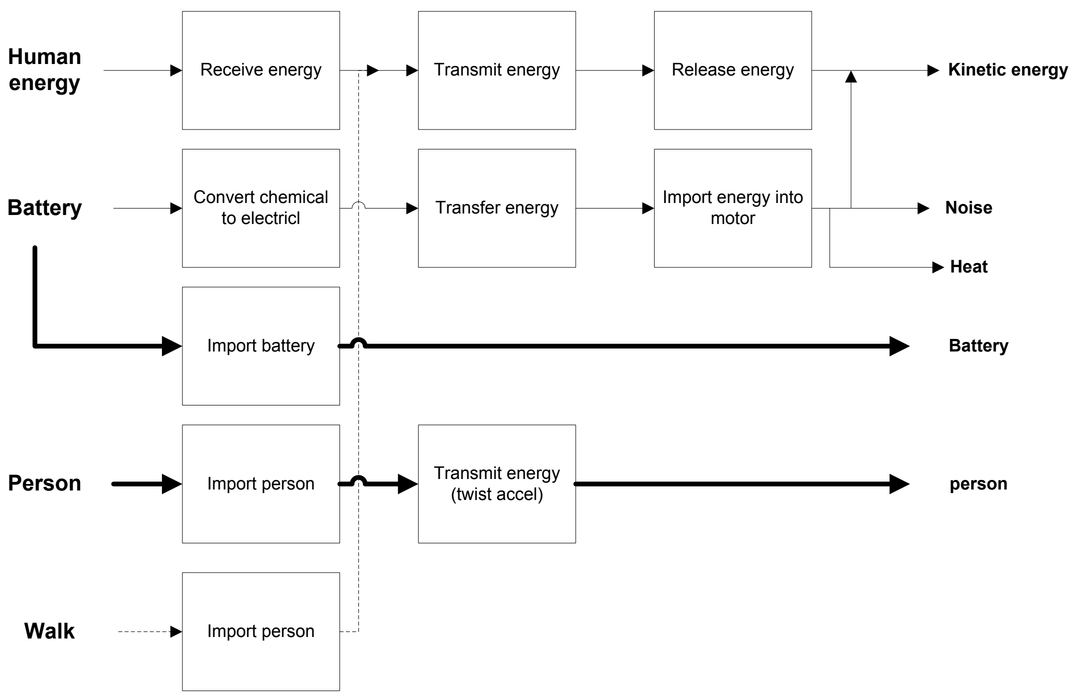
- 1- Aluminum handle
    - Foam grip
    - Plastic molded accessory holder
        - 4- Phillips head screws
    - 1- plastic adjustable locker
        - 1- metal bolt
        - 1- plastic twist knob
    - 1- plastic end cap (connects rods to lower legs)
    - 2- metal rods
    - 1- plastic pivot point
        - 1-metal bolt
- 1- aluminum down tube
    - 1- plastic endcap
    - 1- upper golf bag holder
    - 1- upper velcro golf bag strap
        - 1- metal bolt
    - 1- metal water bottle holder
        - 2- metal rivets
    - 1- plastic lower golf bag holder
        - 1- metal bolt
    - 1- lower clip golf bag strap
    - 1- front wheel clamp/holder
        - 1- spring action locker
        - 2- metal screws
    - 1- metal front wheel arm
    - 1- plastic front wheel
        - 1- metal bolt

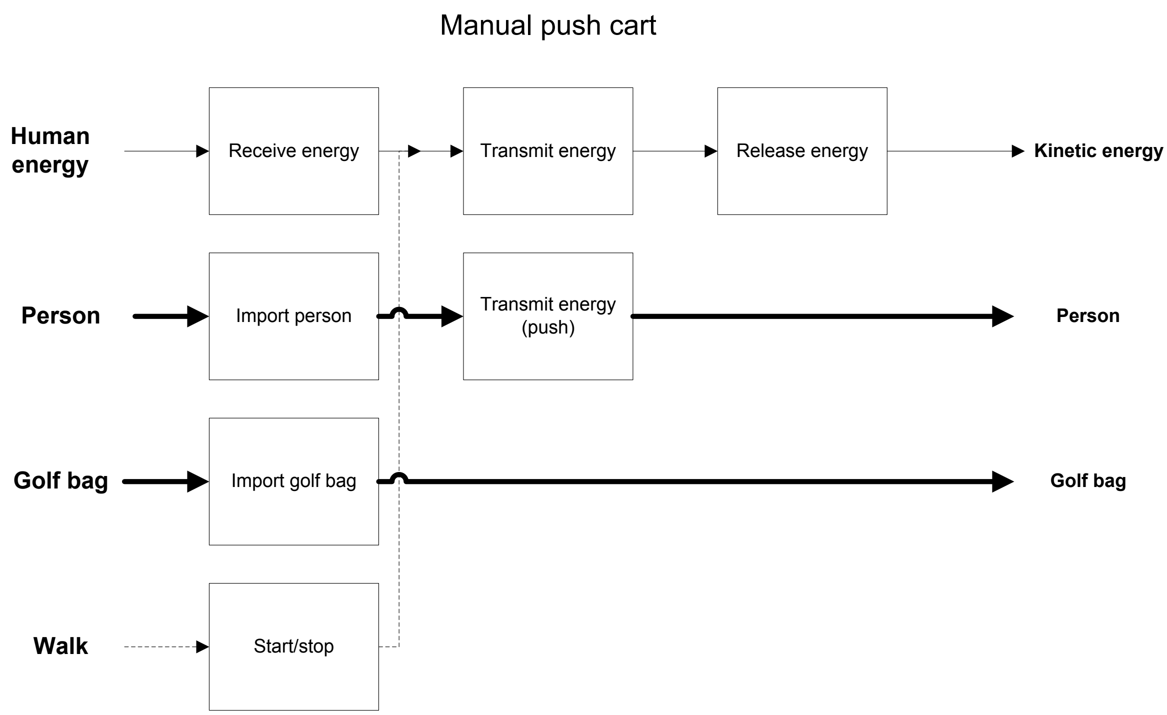
    - 1- lower legs pivot support
        - 4- metal rivets
- 2- large lower legs
        - 2- metal bolts
    - 2- small lower legs
        - 2- metal bolts
    - 1- metal braided cable
        - (metal rods)
    - 2- rear wheel spindles
        - 8- metal bolts
        - 2- rear wheel locking latches
        - 2- rear wheel parking levers
            - 2- metal rivets
    - 2- plastic rear wheels
        - 2- metal/plastic axles with hole for locking
        - Ring of notches on axle for parking leve

APPENDIX E

SCALING PRODUCTS' FUNCTION STRUCTURES

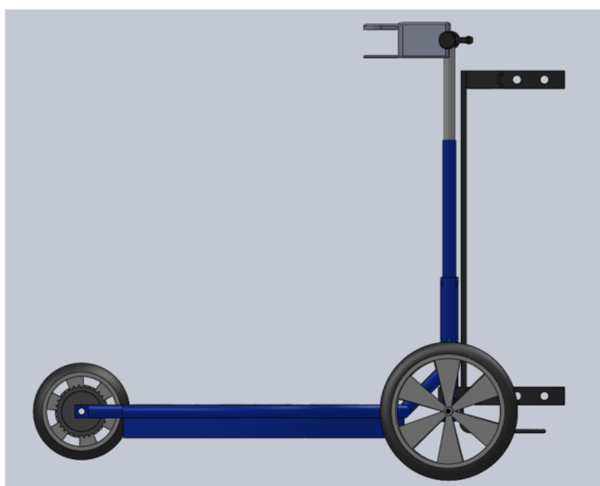
Electrical push cart

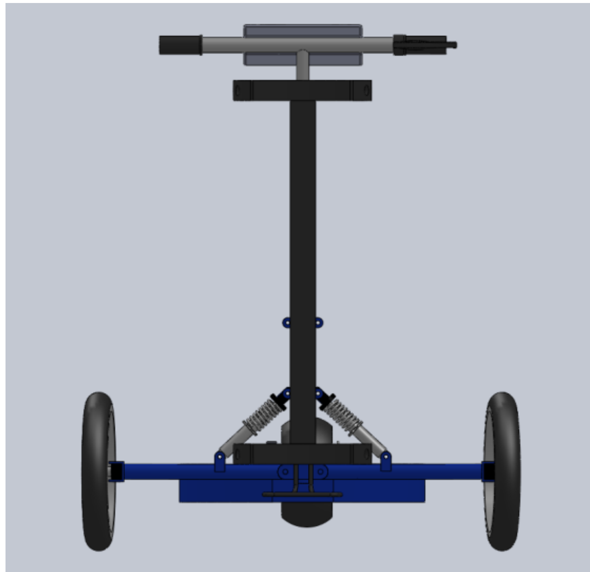


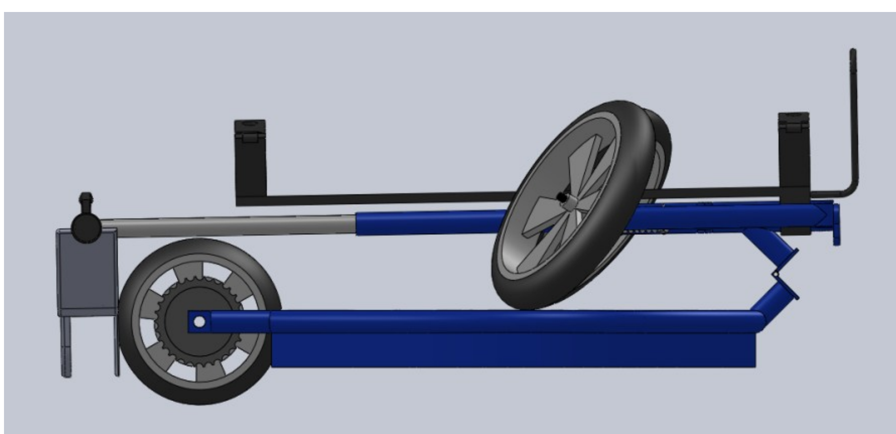

Manual push cart
Human energy
Receive energy
Transmit energy
Release energy
Kinetic energy
Person
Import person
Transmit energy (push)
Person
Golf bag
Import golf bag
Golf bag
Walk
Start/stop

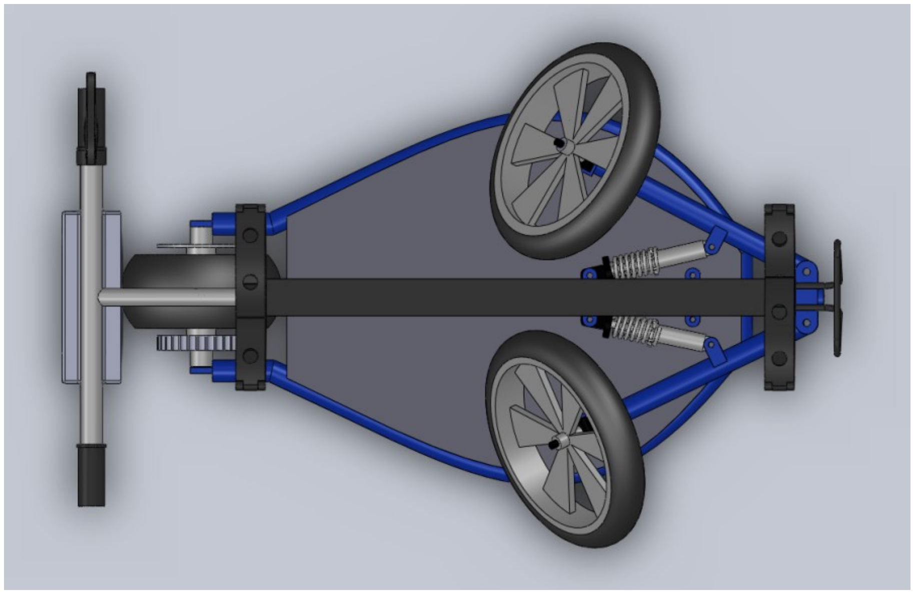
APPENDIX F

FINAL DESIGN SOLIDWORKS RENDERINGS









APPENDIX G

SENIOR DESIGN GOLF SURVEY

Golf Survey

Many people play golf around the world, they travel the golf courses by three different methods; walking plus carrying there bag, walking with a push cart, and using a golf cart. What if there was an alternative method to getting around the golf course that would benefit all age group of golfers? Please fill out the survey below to help use design such an object to benefit golfers.

1. Your age: ____________ (Please Circle One) Male / Female
2. How often do you play golf a week?

1 2 3 4 5 6
7or more

3. On average how much do you spend on playing each month?__________________

4. When you play golf, do you include the cart fees, do you use a push cart, or do you walk through the golf course? (Please Circle One)

Golf Cart / Push Cart / Walk

5. If there was an alternative to using a golf cart, would you be interested in purchasing such a product? (Please Circle One)

Yes / No

6. If a motorized cart was invented that a person could ride, would you be interested in purchasing it? (Please Circle One)

Yes / No

7. How much would you spend on such an object? __________

8. Do you think this would benefit all age groups of golfers? (Please Circle One)

Yes / No

9. What features would you like if such an object was created?

*Thank you for taking the time for filling out the survey

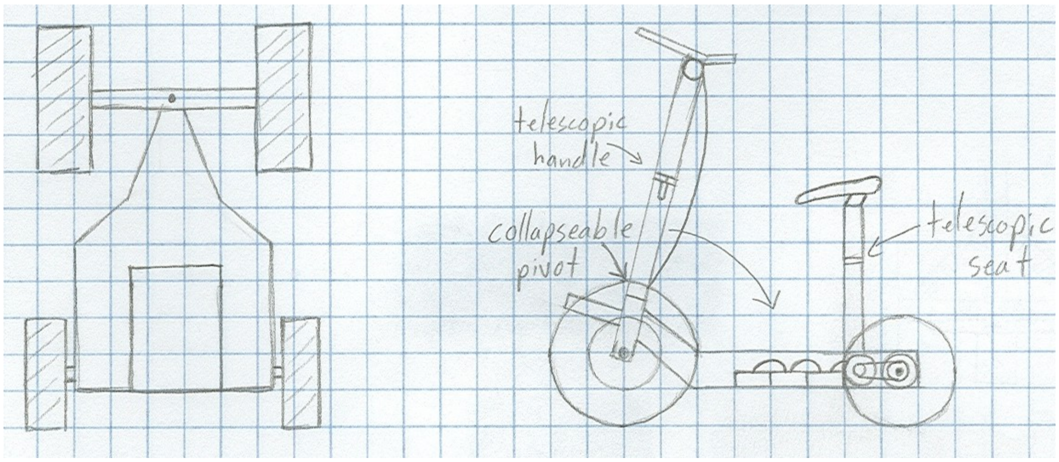
APPENDIX H

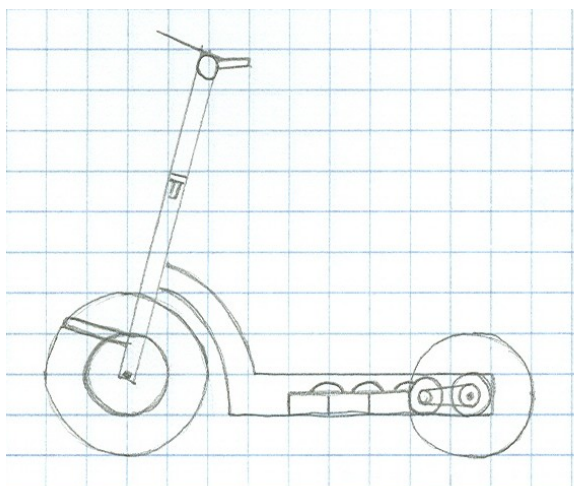
SENIOR DESIGN DECISION MATRIX

Requirements																																																								Total	Percent %
Light weight	0	0	0	1	1	1	1	1	1	1																																														7	12.73
Compact	1										0	0	1	1	1	1	1	1	1																																					8	14.55
Easy to use		1									1									1	1	1	1	1	1	1	1																													10	18.18
Comfortable			1									1								0								1	1	1	1	1	1	1																						9	16.36
Affordable				0									0								0							0							1	0	0	1	1	1																4	7.27
Appearance					0									0								0							0						0						0	0	0	0	1											1	1.82
Low Maintenance						0									0								0							0						1					1					0	1	1	1							5	9.09
Durability							0									0								0							0						1					1				1				1	1	1				6	10.91
Fast								0									0								0							0						0					1				0			0			1	1		3	5.45
Fast Charge Time									0									0								0							0						0					1				0			0		0		1	2	3.64
Accessories										0									0								0							0						0					0				0			0		0	0	0	0.00

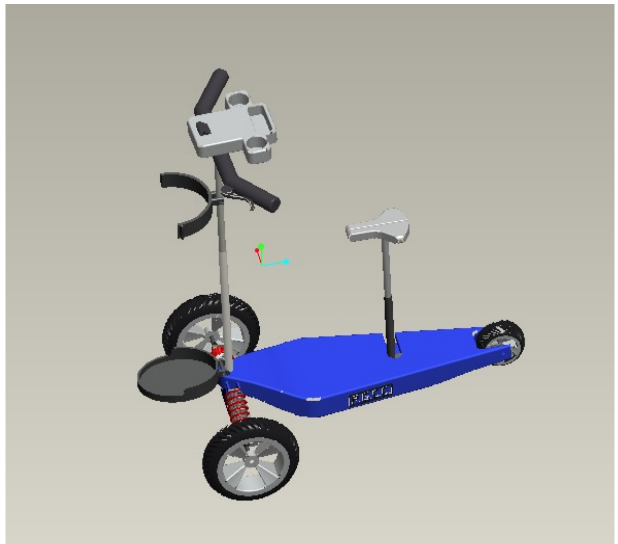
APPENDIX I

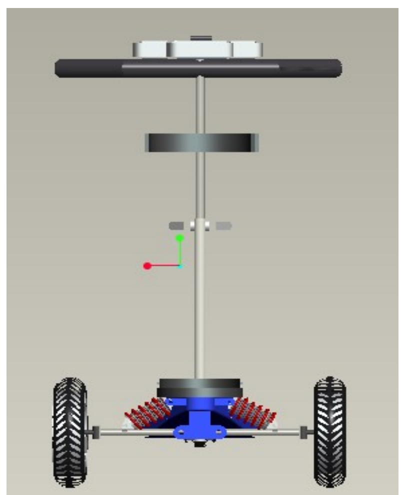
SENIOR DESIGN CONCEPT DRAWINGS

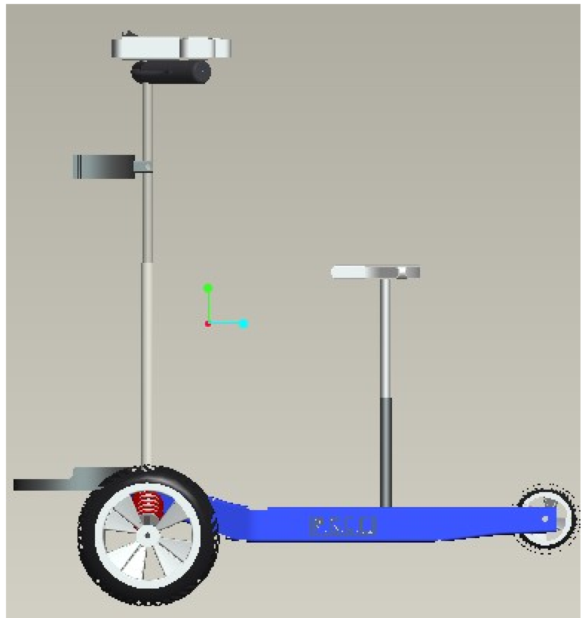




SENIOR DESIGN PRO-ENGINEER RENDERINGS







VITA

Angel Gerardo Perez obtained his Bachelor of Science degree in mechanical engineering from The University of Texas Pan American in December 2008. He pursued graduate studies at Texas A&M University in mechanical engineering and received his Master of Science degree in August 2011. His research interest includes design-by-analogy and idea generation.

Permanent Address: Department of Mechanical Engineering, ENPH, 3123

TAMU, College Station, Texas 77843, USA.

Email: agperez65@tamu.edu