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Application of DFX Methods to a Gait Rehabilitation System

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APPLICATION OF DFX METHODS TO A GAIT REHABILITATION SYSTEM

by

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GAIT REHABILITATION SYSTEM

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Walking is an important physical activity that offers major health benefits for those who are able to perform the task. However, there are millions of people worldwide who have lost the ability to walk from physical accidents or a disease which limits the ability for them to use their legs. Often these patients use gait therapy to learn how to walk again. During this gait therapy, a physical therapist may use gait rehabilitation machines to assist the patient in learning to walk in a correct gait path.

Two gait rehabilitation machine iterations were designed to produce an effective rehabilitation machine that could be used for both pediatric and adult use. The second iteration was designed based on the failures of the first design. The goal was to design a machine that is adjustable between pediatric and adult patients and to be cost effective for small clinics and in-home patient use. Design for Manufacture (DFM) and Design for Assembly (DFA) are two tools that can be applied to a product during the design stage of the products life to ensure the product is designed to be cost efficient. However, when the aforementioned designs were made, DFM and DFA principles were not fully applied in the design stage and possible advantages of using them were missed during the design and production of the two rehabilitation machines.

The goal of this study is to show the potential advantages of applying DFM and DFA into the design process through the comparison of a DFM/DFA analysis of the gait rehabilitative device iterations. After a DFM/DFA analysis was made of both design iterations it was found that there was a 40.04% cost reduction in manufacturing and assembling of Design 2 as compared to Design 1. Therefore, it was concluded that Design 2 was a more cost effective design than Design 1. This study also highlights areas for improvement in the current design iteration.

DEDICATION

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CHAPTER 1 – INTRODUCTION

Walking is one of the most important physical attributes a human being possesses. Having the ability to walk gives a person freedom and allows them to explore the world around them. Walking is also a great form of exercise, especially if one can run in addition to walking, and allows humans to be physically healthy and active. However, according to [1] not being able to walk and be mobile can have a lot of negative physical and psychological health risks. Some of these physical health problems include an increased risk for blood clots and edema, heartburn and indigestion, kidney stones and osteoporosis resulting from calcium drainage from long bones, changes in hormone balance, bladder infections, pressure ulcers, atrophied muscles, difficulty expanding lungs fully, weakened coughs, and lower back pain. Psychological health risks from immobility include social isolation, depression, anxiety, apathy, mood swings, feelings of helplessness, loss of normal sleep cycles, and delirium [1]. Walking is a true luxury that is often taken for granted by those who have never experienced life without it.

There are millions of people worldwide who do not have the ability to walk, whether it be from a physical injury or some disease which limits the use of their legs. In the United States alone, according to the U.S. Census Bureau, 30.6 million people from the ages 15 and above suffer difficulties with lower body function or mobility. This includes difficulty walking, climbing stairs, and using a cane, crutches, wheelchair or walker. Within those 30.6 million there are about 3.6 million people who use wheelchairs and 11.6 million people who use other devices such as canes or walkers to assist in walking. In addition, about 4.5 million children between the ages 6 and 14 have some sort of disability [2].

Physical therapy for walking, also known as gait therapy, is a process in which a therapist helps a patient learn to walk again through a series of guided tasks. This is important for people who have recently had lower body surgery, injuries, strokes, and illnesses or diseases which affect lower body function. There are different types of therapy that a therapist can use to help a patient learn to walk again through a correct gait trajectory. First is by assisting the patient by manually moving their feet through a gait-like trajectory. Second is to use a body-weight supported treadmill to train the patient. The treadmill assists the therapist in moving the foot through a gait-like trajectory and the patient doesn't have to move. Third is through robotic-assisted gait therapy. This kind of therapy uses automated actuation to assist in moving the patient's foot through a gait-like trajectory. Fourth is through the use of motorized foot-propelling devices, such as elliptical machines. These elliptical machines move the patient's foot through a looping trajectory and require little assistance from the therapist [3].

Gait rehabilitation devices have been developed by researchers to assist therapists and clinicians in helping their patients but many have some drawbacks. One such device is the Lokomat which combines robotic gait orthoses with body-weight supported treadmill systems [4-6]. The Lokomat offers adjustment between adult and pediatric patients. However, the Lokomat is expensive and is not affordable for many small rehabilitation clinics and home health centers [4]. It is also cumbersome and time consuming to set up for each individual patient.

Another gait rehabilitation device which assists in gait therapy is the Intelligently Controlled Assistive Rehabilitation Elliptical (ICARE). The ICARE was developed by researchers at the University of Nebraska-Lincoln and Madonna Rehabilitation Hospital.

The ICARE is a motorized elliptical machine that was modified to move the patient's feet through a gait-like motion [7]. It was designed so that patients with little muscular strength could operate it and patients with a lot of muscular strength could drive the machine themselves [8]. The ICARE is a relatively low cost, ergonomic, and effective machine for gait rehabilitation but was designed only for adult use [7].

Since walking immobility is a serious pediatric issue too, there is a need for an effective gait rehabilitation device for pediatric use. Therefore a pediatric gait rehabilitation device that can also be adjusted for adult use was designed by Stolle [3]. This device was designed to accommodate gait training in a healthcare, rehabilitation, or home-health settings. To achieve this, several primary design goals were established. These goals for the device are to provide a normal gait motion, to be scalable and to accommodate for a stride length between 6 and 40 inches, and be practical for small, low-budget rehabilitation facilities to use without extensive personnel training. Secondary design goals for the device include being adjustable for each leg independently to accommodate for unilateral gait deficiencies, being an affordable and cost-effect device for in-home patients, being operable in relatively smaller spaces, being motorized, being backdrivable so that patients can manually drive the device, and being ergonomic. Two iterations of the rehabilitative device were designed and built [3].

The purpose of this study is to address the affordability design goal and to show how implementing Design for Manufacture (DFM) and Design for Assembly (DFA) into a product's design process can make the process and production more efficient and reduce the overall cost. It is widely accepted that even though only 5% of the final cost of a product is spent on the design of the product, over 70% of the product's cost is determined during the design process. In addition, generally more than 50% of the final cost is incurred from the material used to produce the product [9]. Therefore it is important to find the most efficient way to use this material. A secondary benefit of applying DFM and DFA to the creation of new medical devices is that these methods provide data which can be useful in securing Food and Drug Administration (FDA) approval for putting such devices on the market [10]. The primary role of the FDA with respect to medical devices is to regulate the marketing and commerce of the product and to assure the product's safety and effectiveness [10, 11].

The design of the rehabilitative device was more of a research driven design process, whereas applying DFM and DFA is a more professional or commercially acceptable design approach. In this study two design iterations of a rehabilitative pediatric gait device are evaluated and analyzed using DFM and DFA. The gait device was designed and built using the first design initially but after it was built it was determined that the device was not functional and needed improvements. The designer stated in [3] that the rail was shaky and tall, and its non-functionality was blamed on poor tolerances, misaligned shafts, heavy components, rail weight, and large cam accelerations. Some of these shortcomings relate directly to the need for DFM and DFA methods in the design stage. Therefore a second iteration was designed based on the failures of the first iteration. The goal is to show the potential advantages of applying DFM and DFA into the design process through the comparison of the DFM/DFA analysis of the gait rehabilitative device iterations.

CHAPTER 2 – LITERATURE REVIEW

2.1 History

2.1.1 The Design Process

"The design process is the organization and management of people and the information they develop in the evolution of a product" [12 ch.1]. Every product goes through some sort of design process, whether it is structured or not, before it is put into production and sent to market. In early history a whole product could be designed by a single person, as long as that person had sufficient knowledge of physics, materials and manufacturing processes that would be needed to construct the product. However, when projects got too large and complex, this one-man operation ideology was no longer suitable. One person could no longer have sufficient knowledge and time to handle all of the complexity and manufacturing processes for a typical product. So this required the production to consist of different groups of people who would be responsible for marketing, design, manufacturing, and overall management. Having different groups of people in charge of specific areas in the design process led to what is commonly known as the "over-the-wall" design process. Over-the-wall refers to the idea that it is a one-way communication between groups like throwing information from one group to another over a wall. Often what is produced is not what the customer had in mind, and this is a major downfall of the over-the-wall design process. This single-direction communication method doesn't allow clear communication and understanding between groups. It would benefit the engineers to have better communication with the customer and marketing to get a clear understanding of what is wanted. In addition, the design engineers do not know as much about manufacturing processes as those people who are directly involved in manufacturing, so the manufacturers may know cheaper methods to produce the product. For these reasons this design process method is inefficient and expensive and could result in poor-quality products [12 ch.1].

Due to the inefficiency of the over-the-wall process, the concept of simultaneous engineering broke through in the late 1970s and early 1980s. Simultaneous engineering focused on the development of the manufacturing process with the advancement of the product simultaneously. This process was achieved by having manufacturers be a part of the design team and work with the design engineers throughout the design process. In the 1980s concurrent engineering and in the 1990s integrated product and process design were processes that were built off of the simultaneous design philosophy [12 ch.1].

Since these three design processes are similar, this thesis will focus on concurrent engineering. Groover [13 ch.39] refers to concurrent engineering as "an approach to product design in which companies attempt to reduce the elapsed time required to bring a new product to market by integrating design engineering, manufacturing engineering, and other functions in the company." The main focus is on combining the different teams of people, design tools and techniques, and the information and processes used to develop and manufacture the product. Using teams of people in the concurrent design method to get different people working together during each phase of the design and development of the product eliminates most of the problems that were seen in the over-the-wall method. With the integration of people in design teams, information such as drawings, plans, concept sketches and requirements can easily be shared with the right people at the right time. This is a key point in concurrent engineering. In addition, having people with different views work together helps address the entire life cycle of the product [12 ch.1].

No matter what design philosophy or process is being used, all products go through a life cycle. Different phases of the product's life cycle are grouped into four main areas: product development, production and delivery, product use, and the product's end of life. Before a product is developed there must be an established need for the product. The need for new products comes from either the market need or the designer is designing a new product idea that has yet to be brought to market. However, new design idea projects make up only about 20% of new product developments, meaning about 80% of new products are market driven. Within market driven design projects for a new product is the process of redesigning an existing product. An engineer will redesign an existing product if the market demand is to include new technology or a new model, fix an existing problem, reduce the cost of the product, change the manufacturing process or change the materials used to manufacture the product. There are useful techniques that can be used during production that help in the redesign of existing products. Such techniques include Design for Manufacture (DFM) and Design for Assembly (DFA) [12 ch.4].

2.1.2 DFMA

DFMA, design for manufacture and assembly, is a combination of the two design techniques design for assembly (DFA) and design for manufacture (DFM). Boothroyd, Dewhurst, and Knight [9 ch.1] define DFA as designing a product for the ease of assembly and DFM as designing the collection of parts that form a product for the ease of manufacture. Boothroyd, Dewhurst, and Knight [9 ch.1] also refer to the term manufacture as the manufacturing of individual component parts of a product and, to assemble as joining parts to form a completed product. Boothroyd, Dewhurst, and Knight

[9 ch.1] have listed three main activities for using DFMA: 1) as the basis for concurrent engineering studies to provide guidance to the design team in simplifying the product structure to reduce manufacturing and assembly costs, and to quantify the improvements, 2) as a benchmarking tool to study competitors' products and quantify manufacturing and assembly difficulties and 3) as a should-cost tool to help control costs and to help negotiate suppliers' contracts.

Before understanding how to use DFMA it is important to know why and how it came into existence. DFMA was developed from research on the topic of automatic assembly. In 1963, Geoffrey Boothroyd and Alan Redford, Boothroyd's graduate student, started doing research in this field at Salford University in England. Boothroyd then furthered this research at the University of Massachusetts with his colleagues Corrado Poli and Laurence Murch. In the early 1970s they published a handbook of feeding and orienting techniques for small parts. In order to catalog the various solutions to feeding and orienting techniques a numerical part coding system was developed. The codes pointed to which pages in the handbook showed automatic feeding solutions and also showed which parts were easy and difficult to feed and orient, and those that cannot be fed and oriented automatically. A systematic method was developed to quantify product designs for the ease of automatic assembly so that product designers will have a technique to avoid part shapes that are difficult to feed and orient. Therefore the Design for Automatic Assembly method was developed. Boothroyd and Bill Wilson, his colleague at the University of Massachusetts, visited the National Science Foundation (NSF) to present a proposal on the idea that they could make a contribution to the subject of Product Design for Ease of Manufacture. In 1978 they receive funding for a 3-year research program to study Design for Manufacturability. Boothroyd, as part of his contribution in the research program, pursed his interest in Design for Assembly. He collaborated with Alan Redford and Ken Swift, colleagues of his in England, for the automatic insertion of parts. The analysis method of Design for Manual Assembly was developed by Boothroyd and his students. As part of Bill Wilson's contribution, he studied the initial Selection of Materials and Processes for the manufacture of parts. Design for Manufacture was the third area of study and was contributed by Winston Knight from Oxford University and Corrado Poli. From this research study was born DFA and DFM. [9 ch.1].

2.2 Description of DFM and DFA

The design stage during the life of a product is very important because many of the decisions that impact the development and the cost of the product are made in this stage. In fact, according to many studies, around 70-80% of a product's life cycle costs are decided during the design stage. Many design methods or concepts have been developed over the years in order to increase the efficiency of the design stage of a product and to decrease the total cost and time to market for the product. These methods have come to be known as part of the Design for X (DFX) methods. DFX can be split up into three categories: 1) product scope, 2) system scope, and 3) eco-system scope [14]. Design methods included in DFX are design for manufacture, assembly, quality, validation, reliability, quality, usability, maintenance, environment, obsolescence and recyclability [14, 11]. It is important to incorporate these methods with a concurrent engineering approach so that the product and its manufacturing processes can be improved simultaneously during the design stage. This thesis, however, focuses on DFM and DFA.

Design for Manufacture (DFM) and Design for Assembly (DFA) are techniques which are used to positively influence the manufacturability of a product. DFM and DFA are two different techniques with their own set of guidelines and principles but since they are similar they are often coupled together into one technique known as DFMA or Design for Manufacture and Assembly. Groover [13 ch.39] defines design for manufacture and assembly as "an approach to product design that systematically includes considerations of manufacturability and assemblability in the design." To most effectively incorporate DFMA into a company the company needs to make organizational changes to implement concurrent engineering. Concurrent engineering allows engineers to better interact and communicate the principles and guidelines of DFMA in design teams. These principles and guidelines help the design team design a product for maximum manufacturability. Bakerjian and Mitchell [15], and Corbett et al. [16] cites typical benefits from using DFMA guidelines. They are 1) shorter time to bring the product to market, 2) smoother transition into production, 3) fewer components in the final product, 4) easier assembly, 5) lower production costs, 6) higher product quality, and 7) greater customer satisfaction [13 ch.39].

2.2.1 DFM

Design for Manufacture or Design for Manufacturability, is a process that has been developed with the goal of reducing manufacturing cost and improving product quality [17 ch.9]. The main focus in DFM is to find the best manufacturing process for the part and that the part form fits the selected manufacturing process. [12 ch.12]. DFM is proof of the importance of concurrent engineering. DFM can be considered the first step in manufacturing but is implemented during the design of the product. To achieve the goals of DFM, manufacturing engineers need to be a part of the design team from the beginning. There are a general set of guidelines for DFM that ensure the designer will get the most out of the process [17 ch.9].

Guidelines:

- Reduce the overall number of parts
- Use standardized components
- Use common parts across product lines
- Design parts to be multifunctional
- Design parts for ease of fabrication
- Avoid overly tight tolerances
- Avoid secondary operations
- Make good use of processes' special characteristics

Design rules that should be used to get the most out of DFM include [17 ch.9]:

- Adequate distance between holes
- Write specific notes on engineering drawings
- Set dimensions from a specific surface or point and from a single datum
- Design the part for minimum weight while still meeting strength and stiffness requirements
- Design parts to be fabricated using general purpose tooling
- Use generous fillets and radii
- Design parts to avoid repositioning during machining

The first step in lowering manufacturing cost through the use of DFM is to reduce the total number of parts. Having multiple parts that need to be machined increases the machining time and subsequently increases machining cost. When a part is eliminated from a design it no longer carries any penalties with it. Therefore the eliminated part costs nothing. A part can be eliminated if:

- The part doesn't move relative to another part
- The part doesn't need to be made of a different material relative to neighboring parts
- Assembly/disassembly is possible without it

A related approach is to design parts to be multifunctional. A way to eliminate parts is to combine them into one part that can satisfy the functions of the separate parts. This is an efficient way to eliminate parts and get the most out of the design [17 ch.9].

Using standardized components minimizes cost and improves quality because standard commercially available components are used in the design. Since these components are commercially standardized and widely used, the life and reliability of the components has already been established. The designer can reduce cost by buying the components in large quantities to get discounts, reduced design time from not having to design special components, and from not having to use additional machining and tooling cost to produce special components [17 ch.9]. However, it can be harmful to overuse standardization. It can prevent design innovation if a designer or company uses standard components to an extreme. Lots of breakthrough success can be attributed from breaking away from standard components and innovating new ideas [9 ch.7].

In relation to using standardized components, it is preferred to use parts that are available to the manufacturer. Whether you are using special parts that have already been designed and machined or standard parts, it is efficient to use parts that are abundantly available. Using common parts on multiple products greatly reduces inventory cost [17 ch.9].

It is efficient to use the cheapest material that satisfies all of the functional requirements. If possible the material should be produced using machining processes that produce near net shape. Such processes include casting, extrusion, deep drawing, blanking, and forging. Preshaping the material to a near net shape can help to minimize the amount of machining done to a material [17 ch.9, 9 ch.7].

When setting tolerances for parts, the designer should approach this with great care. The loosest tolerances and roughest surfaces that would give acceptable performance for operating surfaces should be specified. Tighter tolerances and smoother surfaces increase the machining cost because secondary finishing operations, precise tooling, and skilled workers have to be used to achieve the tolerances and surface roughness. This also increases the total machining time. As a guide to the difficulty of machining specified tolerances, Boothroyd, Dewhurst, and Knight [9 ch.7] stated:

1. Tolerances from 0.127 - 0.25 mm (0.005 - 0.01 in) are readily obtained
2. Tolerances from 0.025 - 0.05 mm (0.001-0.002 in) are slightly more difficult to obtain and increase production costs.
3. Tolerances 0.0127 mm (0.0005 in) or smaller require good equipment and skilled operators and significantly add to production costs.

2.2.2 DFA

After parts are manufactured in an efficient way, they need to be assembled efficiently. DFA measures the efficiency with which a product can be assembled. To assemble a product, a person, machine or robot must retrieve, handle and join the parts to create the final product. Since most products are assembled from multiple parts, this assembly process takes time which costs money. The cost of assembling a product is a significant part of the labor cost in manufacturing. If a designer can decrease the number of parts in an efficient way he will decrease the time for assembly which will result in lower labor cost and save money. It will also decrease the product time to market [12 ch.12]. There are general DFA guidelines a designer can follow which will lower the cost of assembly and will make the assembly process easier and more efficient.

Guidelines:

- Reduce the overall number of parts
- Avoid the use of separate fasteners
- Design the product with a stationary base to build upon
- Design for an efficient assembly sequence
- Avoid tangling, nesting, and flexible components
- Design components for a specific type of retrieval, handling, and insertion
- Design components with end-to-end and rotational symmetry
- Design components which are not symmetric to be clearly asymmetric
- Minimize assembly directions
- Maximize component compliance in assembly
- Maximize component accessibility [12 ch.12, 17 ch.9]

These guidelines can be split up into four sections which are: assembly efficiency, component retrieval, component handling, and component insertion [12 ch.12].

A) Assembly Efficiency

The first step in making the assembly process efficient is to decrease the total number of parts. Having fewer parts to assemble decreases the assembly time and can save money in assembly cost. To evaluate the parts count in the current design to see if there is room for improvement the designer needs to examine each part and decide if that part is necessary or not. If a part doesn't need to be separate from another part then theoretically the parts can be combined. There are three criteria, mentioned earlier, for a part to be separate [12 ch.12, 17 ch.9].

After the designer has examined each part and decided if it was necessary or not, he has now found the theoretical minimum number of components for the design. After the designer has found the theoretical minimum number of components, he can then analyze the assembly of the current design. The improvement potential of the design can now be calculated by using equation (1) [12 ch.12].

$$Improvement\ potential = \frac{\binom{actual\ number\ of}{components} - \binom{theoretical\ minimum}{number\ of\ components}}{actual\ number\ of\ components}\ x\ 100 \quad (1)$$

This equation helps the designer to rate the design based on a percentage and determine if there is potential for improvement. If improvement potential is:

- Less than 10%, the design is outstanding
- Between 11-20%, the design is very good
- Between 20-40%, the design is good
- Between 40-60%, the design is fair
- Greater than 60%, the design is poor

After a product is redesigned a similar equation to equation (1) can be used to rate the redesigns actual improvement [12 ch.12].

$$Actual\ Improvement\ = \frac{\begin{pmatrix} number\ of\ components \\ in\ the\ inital\ design \end{pmatrix} - \begin{pmatrix} number\ of\ components \\ in\ the\ redesign \end{pmatrix}}{number\ of\ components\ in\ the\ initial\ design}\ x\ 100 \qquad (2)$$

The designer can also calculate the design efficiency based on assembly time once the theoretical number of parts is found. Using equation (3) [17 ch.9, 9 ch.3] allows the designer to calculate design efficiency.

$$Design\ Efficiency = \frac{t_a\, N_{min}}{t_{ma}} \qquad (3)$$

N_{min} is the theoretical minimum number of parts, t_{ma} is the estimated total assembly time for the product and t_a is the theoretical assembly time for one part, which is the average time for a part that is not difficult to handle, insert or fasten. t_a equals 3 seconds [9 ch.3].

It may not always be possible to reach the theoretical number of parts. However, trying to decrease the number of parts in a design by combining parts together can result in a conflict with DFM guidelines. Combining parts can create complex geometries with high tolerances that can be difficult to machine and result in an increase in machining cost. Therefore the designer needs to be aware of this conflict when he is redesigning the product [12 ch.12].

A great way to reduce the total number of parts in a design is by reducing or eliminating the need to use separate fasteners. Separate fasteners can carry a lot of penalties and cost with them. When a part is eliminated it carries no penalty [17 ch.9]. Using fasteners increases the time in an assembly because they are an additional part that needs to be handled, especially in cases like a bolt where there is usually a nut associated with it. The nut increases handling time and usually requires an extra tool to be used. On average the handling time of a fastener is usually 10 seconds per fastener. Fasteners are extra parts that need to be purchased and stored in inventory and then assembled which adds extra cost to the total. Fasteners can also lead to failure in the design because they are a point of concentrated stress. For these reasons it is a good idea to avoid using separate fasteners as much as possible. However, fasteners can be important in a design if there is a need for maintenance and the product needs to be disassembled [12 ch.12]. Standard fasteners should be used when fasteners are needed [17 ch.9]. The designer should justify their reasoning when eliminating parts [12 ch.12].

Using a single part as the base for all other parts to be built upon it will help ensure an efficient assembly. It helps avoid reorienting parts during assembly and will decrease time of assembly. The base should also not be reoriented during assembly. An ideal assembly would be building up from the base piece by piece in a single direction like a pyramid [12 ch.12].

It is important to make the assembly sequence as efficient as possible. It is desirable to simplify the design so that fewer surfaces need to be machined and all work and assembly can be done on each surface before moving on to the next one [17 ch.9]. One should avoid creating multiple subassemblies which have to be joined to the final assembly later, as well as, awkward and obstructed lines of assembly. In many cases if the assembly sequence is easy for a robot to assemble it will be easy for manual assembly. Humans are often able to move themselves more easily than a robot [12 ch.12].

B) Component Retrieval

It is important to minimize handling as much as possible and therefore the retrieval of the components needs to be as efficient as possible. Tangling, nesting, and flexibility characteristics can make it difficult to retrieve components. It is very difficult to pick up a component individually out of a bin if it has any one of these characteristics. When components get jammed inside of each other it is considered nesting. When possible, one should avoid using flexible components because they can be hard to retrieve. Rather, components should experience negligible deflection under loading typical of assembly operations [12 ch.12].

Components need to be designed for a specific type of assembly. As mentioned before there are three different assembly methods that need to be considered while designing a component: manual, robotic, and automatic assembly. These different methods have different ways in which to grasp or retrieve the components. In manual assembly a human worker grabs a part at their workstation, orients and positions the part for insertion. The parts are then inserted together and may be fastened using tools. In automatic assembly the parts are handled by a parts feeder that feeds the correctly oriented parts to an automatic workhead for insertion [17 ch.9]. In robotic assembly, robots use different types of end effectors to retrieve the components [12 ch.12].The component needs to be designed for the most appropriate method of assembly. Generally for manual assembly to be the most economical method of assembly the annual volume of the product should be less than 250,000. If the annual product volume ranges from 250,000 to 2 million then robotic assembly is the most economical method. If the annual product volume exceeds 2 million then special purpose machines are the most economical choice [12 ch.12].

C) Component Handling

To make assembly more efficient the components should be designed to be symmetrical so they do not need to be reoriented. A component should be designed to be end-to-end symmetrical and symmetrical about the axis of insertion (rotational symmetry). End-to-end means the component can be inserted from either end. If a component is restricted to only be inserted one way, then after retrieval it must be oriented to be inserted in that way. This increases the time and complexity of assembly. If the component was perfectly symmetrical then it doesn't have to be specifically oriented and handling becomes easier [12 ch.12].

If the cost to modify the components is more than the reduced assembly cost then the designer might want to reconsider the modifications. Instead the designer could make the part clearly asymmetric [12 ch.12].

D) Component Insertion

To make component insertion more efficient, the components should all be designed to be inserted in a straight line from a single direction. This will reduce reorientation of the base and any other additional assembly motion. If this is done in a top-down manner along the downward direction, then the pieces will fall together from above and will be assisted by gravity. To make insertion even easier and so that excessive force doesn't have to be used, the component should be designed to be self-aligning. This can be accomplished by using relaxed tolerances and by making use of generous tapers, chamfers and leads [12 ch.12, 17 ch.9].

Another consideration while designing a component is to make the component accessible for assembly and maintenance. There must be necessary room to use tools to assemble and disassemble the components with ease [12 ch.12].

2.3 Related Software

After the 1960s, when tabular design for assembly methods were created, researchers realized that the speed and ease of assembly analysis could be improved by creating computer software to implement DFA. From this research spawned different DFA software. Two methods that were created are Boothroyd and Dewhurst's Design for Manufacturing and Assembly software and the Mathieson-Summers connective-complexity algorithm. This section of the paper will describe how each method is used and how effective an analysis each can obtain [18].

2.3.1 Boothroyd and Dewhurst's DFMA

Boothroyd and Dewhurst's DFMA software requires the user to answer specific questions about the assembly of the product, the subassemblies of the product, and the components of the product. The answers to these questions provide the software with specific information so that a DFA analysis can be made. There are two main sections of the analysis: determining the theoretical minimum number of components and determining product assembly times and costs. When the theoretical minimum number of components is found, it shows the designer what parts can theoretically be eliminated from the assembly [18].

After the theoretical minimum number is found the design efficiency, which shows the designer how efficient the product is with respect to DFA, is calculated. This is a way the designer can document the improvements of the product before and after DFA.

The second part of the DFA analysis is concerned with estimating the assembly time and cost of the product. This estimation is done by determining the size, symmetry, handling and insertion difficulties of each part. The designer has to choose from multiple options for each area to determine the correct assembly time of the part. The estimated assembly time can be used to find a cost estimate of the assembly. [18]

The DFMA software requires the designer to evaluate eight different areas per part: product definition, securing method, minimum part criteria, envelope dimensions, insertion and orientation symmetry, handling difficulties, insertion difficulties, and fetching distance. From these eight areas the designer has to answer a total of 49 questions per part. This can be a long and tedious process for complex products with a lot of parts. The software uses this information to automatically make assembly time estimations for the specified product. Owensby et al. [18] determined that 16 of the 49 questions are subjective or are opinionated questions. This means that 33% of the total analysis is based on the designer's opinion. When this software is used by different designers for the same product the designer may answer the subjective questions differently which can result in different assembly time estimations. This reduces the repeatability, consistency, and accuracy of the method. However, it does provide the designer with validated assembly times and identifies eleven areas to focus on for redesign. These are critical for an effective DFA method [18].

2.3.2 Mathieson-Summers

Mathieson-Summers connective-complexity method uses the physical connectivity between the parts in the assembly to predict assembly times. Every part in the assembly is evaluated by determining what other parts the part is connected to and how they are connected. There are four general types of connection: surface contact, fasteners, snap/press/interference fits, and other connections. An assembly bi-partite graph is then created to represent the assembly architecture. The bi-partite graph is a graph of two independent sets, the parts in the assembly and the connections between the parts. It then uses previous predicted assembly times, which are based on the data in the Boothroyd Dewhurst DFA tables, and maps graph properties of the assembly architectures to the assembly times. Future assembly times of different architectures are then predicted using a historical regression model [18].

To complete the analysis of this method only two types of information are needed from the user. These are what parts is a part connected to and how are they connected. Only five questions are asked to obtain this information and they are all objective. Once the designer has decided that a part is connected to another then all that has to be done is decide which of the four connection types are used. These questions are quick and easy to answer, so it can be a relatively quick method. In fact, a study done by Owensby et al. [18] determined that the Mathieson-Summers method could be implemented about 25% faster than Boothroyd and Dewhurst's DFMA method. Moreover, since the method only takes hours to implement, according to the study done by Owensby et al. [18], and it only requires the designer to answer five objective questions, it should provide a repeatable and consistent analysis between different people. However, this method does not provide any redesign features to improve the product assembly, and the predicted assembly times provided by the method, in the study done by Owensby et al. [18], cannot be accepted as correct because they have not been fully validated yet. Future work needs to be done on this method such as creating a set of formalized rules and validating the assembly times [18].

CHAPTER 3 – MACHINING

To create the rehabilitative gait machines [3] a certain amount of machining had to be done to some parts in order for those parts to be able to be assembled with other parts. Groover [13 ch.23] defines machining as "a manufacturing process in which a cutting tool is used to remove excess material from a workpart so that the remaining material is the desired part shape." The cutting tool removes material from the work piece by forming a chip through shear deformation of the work material. After the chip is removed a new surface is left behind. In order for shear deformation to occur there needs to be relative motion between the cutting tool and the work material. In most machining operations relative motion is accomplished by a primary motion called the speed and a secondary motion called the feed. The desired shape of the work surface is affected by the shape of the tool and it is penetration into the work surface, which is achieved by a combination of the speed and feed [13 ch.23].

Machining is primarily associated with shaping metals but it can also be applied to plastics and plastic composites. Ceramics are difficult to machine because of their high hardness and brittleness but they can be machined by abrasive machining processes. Any regular geometry such as a flat plane, round hole, or cylinder can be cut by a machining operation. In addition, almost any shape can be produced by combining several machining operations. Machining can achieve tolerances less than 0.001 in (0.025 mm) and surface finishes better than 16 µin (0.4 µm). Because of these characteristics machining is generally used to produce the final geometry, dimensions and surface finish of a part [13 ch.23].

There are many different kinds of machining operations that can all be used to created different shapes, dimensions, and surface finishes. However, each operation has its own limitations in what geometries, tolerances and surface finishes can be achieved. Processes which are considered to be machining operations include: turning, drilling, milling, shaping, planing, broaching, sawing, and machining operations that use abrasives to cut material, such as grinding. The two most common types which were used during this project to produce in-house machined parts were drilling and sawing [13 ch.23].

3.1 Drilling

Groover [13 ch.25] defines drilling as “a machining operation used to create a round hole in a work part.” Drilling is most often performed on a drill press but can be also be performed by other machining operations. For example, turning a workpiece into a stationary drill bit is another way to perform a drilling operation. During most drilling operations a rotating cylindrical tool with two cutting edges, called a drill or drill bit, is fed into a stationary work piece to form a hole. The hole’s diameter matches that of the drill bit [13 ch.25].

The most common type of drill bit is called the twist drill and comes in diameters ranging from 0.006 in (0.15mm) to 3.0 in (75 mm). Twist drills are commonly limited to drilling hole depths at a maximum of four times its diameter. The body of the drill has two spiral flutes cut into it and they are responsible for the extraction of chips out of the hole. A typical angle for spiral flutes, also called the helix angle, is around 30°. The point of the drill is generally a cone shape having a typical angle of 118°. Drill points most commonly have a chiseled edge with two cutting edges that lead into the flutes. Chips are formed from the relative motion between the cutting edges and the workpiece. Relative motion is accomplished from the drill bit being rotated and fed into the material [13 ch.25].

3.2 Sawing

According to Groover [13 ch.25], “Sawing is a process in which a narrow slit is cut into the work by a tool consisting of a series of narrowly spaced teeth.” Sawing is generally used to perform cutting operations. Chips are formed from the relative motion between the stationary work material and the moving saw blade. For this study a bandsaw was used to machine materials [13 ch.25].

Bandsawing is a type of sawing where the saw blade, also known as a bandsaw blade, is a flexible loop with teeth on one edge. The blade is continuously driven through the work material by a pulley-like drive mechanism in the bandsaw machine. The blade travels in a continuous linear motion. Bandsaws are classified by the direction, vertical or horizontal, of the blade motion during cutting. Vertical bandsaws are commonly used to perform cutoff, contouring, and slotting operations while horizontal bandsaws are used for primarily cutoff operations. Vertical bandsaws can be operated either manually or automatically. In manually operation the material is fed into the saw blade by the operator and in automatic operation the material is fed automatically through the blade [13 ch.25].

The saw blades in all sawing operations have common features. The blade has a tooth form, tooth spacing, and a tooth set. The tooth form is concerned with the rake angle, clearance angle, tooth spacing, and other geometrical features of the cutting tooth. Tooth spacing is the distance between adjacent teeth and is responsible for the size of the teeth and the size of the gullet between teeth on the blade [13 ch25]. The tooth set, as defined by Groover [13 ch.25], “permits the kerf cut by the saw blade to be wider than the width of the blade itself.” This allows the blade to pass through the workpiece without binding.

3.3 Manufacturing Time Estimate

In order to make a cost estimate on the machining required for the manufacture of two different designs of a rehabilitative gait machine, the total time it took to machine different parts needs to be calculated. As mentioned above, the two machining processes that were used to manufacture parts in-house were drilling and sawing. The parts that were manufactured in-house were constructed from angle iron and square tube steel. As can be seen from the Bill of Materials (BOM) in Appendices A and B, the angle iron used was 1.25” by 1.25” with thickness 0.125” and the square tube steel used was 1” by 1” with thickness of 0.12”. The angle iron meets the ASTM A36 standard. The square tube steel meets ASTM A500 and is 1005-1026 steel [19]. Theoretical drilling and sawing machining times were calculated to make an estimate on the total machining time of the parts. An experiment of drilling, using an upright drill press, and sawing, using a horizontal hand bandsaw, was also performed to get a more realistic estimate on the time it took to perform these machining operations. T_m, machining time, is the time the drill bit or saw blade is engaged in machining the material.

3.3.1 Drilling

For drilling a through hole, which is when the drill bit exits the opposite side of the work, the machining time can be calculated using the equation [13 ch25]:

$$T_m = \frac{t + A}{f_r} \tag{4}$$

where t is the work material thickness (in.), f_r is the feed rate (in./min) of the drill into the work material and A is an approach allowance that accounts for the drill point angle. "A" represents the distance the drill must travel into the work material before it reaches its full diameter and is measured in inches. "A" can be calculated using the equation [13 ch25]:

$$A = 0.5Dtan\left(90 - \frac{\theta}{2}\right) \tag{5}$$

where D is the diameter (in) of the drill bit, and θ is the drill point angle, typically equal to 118°.

The feed rate, f_r, can be calculated using the equation [13 ch25]:

$$f_r = Nf \tag{6}$$

where N is the spindle speed (rev/min) and f is the feed (in./rev). N can be calculated using the equation [13 ch25]:

$$N = \frac{v}{\pi D} \tag{7}$$

where v is the cutting speed (in./min) and D is the diameter (in) of the drill.

Cutting speeds can be found for drilling various materials in [20]. These are traditional Handbook cutting speeds (given in feet per minute) used for drilling with high speed steel (HSS) drill bits. These speeds can then be converted from feet per minute to inches per minute by multiplying the value by 12. The cutting speed can then be inserted into the previous equations to find the machining time. Also in the Machinery's Handbook [20] one can find feed (in/rev) ranges for various drill bit diameter ranges. Viking Drill [21], states as a general rule feed equals 0.001 inch per revolution for every 1/16 inch of drill diameter, plus or minus 0.001 inch on the total. This general rule is consistent with the feed ranges listed in [20].

A) Theoretical Drilling Time

Table 1. Theoretical Drilling Parameters

	Angle Iron	Square Tube Steel
Spindle Speed	1100 rev/min	1100 rev/min
Feed Rate	5.5 in/min	5.5 in/min
Approach Distance	0.094 in	0.188 in
Machining Time	0.0398 min	0.778 min

i) Angle Iron

The drill bits used for cutting the material are assumed to be HSS twist drill bits with tip angles equaling 118°. The angle iron is an ASTM A36 material and is assumed to have hardness values similar to 1018 carbon steel. From [22], an ASTM A36 material has Brinell hardness values ranging from 119-159. From [20], the cutting speed of a 1018 carbon steel having Brinell hardness values ranging from 125-175 is 90 feet per minute (fpm) or 1080 in./min. So the cutting speed, v, for drilling into angle iron equals 1080 in./min.

Holes with a diameter of 5/16" are to be drilled into angle iron that has a thickness of 0.125 inches. The drill bit that is used is a 5/16" diameter HSS twist drill bit. A diameter of 5/16" was used because it is a common size that can be used in a standard setting.

Using the general rule stated in [21], the feed for a 5/16 drill bit equals 0.005 in./rev. This feed is used to calculate the feed rate. Once the feed rate and approach distance are known and the thickness of the angle iron is 0.125 inches, the machining time for drilling can then be found. Table 1 presents these machining parameters and the time to drill a single hole into angle iron using a drill press. These values were calculated using equations (4) through (7). Therefore, as can be seen from Table 1, the machining time equals 0.0398 minutes or 2.39 seconds.

ii) Square Tube Steel

The drill bits used for cutting the material are assumed to be HSS twist drill bits with tip angles equaling 118°. Square tube steel is an ASTM A500 material made from low carbon steel and it is assumed that it has hardness values similar to 1018 carbon steel. From [20], the cutting speed of a 1018 carbon steel having Brinell hardness values ranging from 125-175 is 90 feet per minute (fpm) or 1080 in./min. So the cutting speed, v, for drilling into square tube steel equals 1080 in./min.

Holes with a diameter of 5/16" are to be drilled into the square tube steel that has a thickness of 0.12 inches. Therefore the drill bit that is used is a 5/16" diameter HSS twist drill bit. A diameter of 5/16" was used because it is a common size that can be used a standard setting.

Using the general rule stated in [21], the feed for a 5/16 drill bit equals 0.005 in./rev. The feed is used to calculate the feed rate. Once the feed rate and approach distance are found the machining time to drill a single hole into a piece of square tube steel can then be found. However, square tube steel is hollow and when drilling straight through it the drill bit will encounter two approach distances (the approach of drilling through the top at the beginning of the drilling operation and the approach into the bottom side of the square tube after drilling through the top). The drill bit will also cut through the thickness, which equals 0.12 inches, twice. Therefore the thickness, t, equals 0.24 inches. Table 1 presents the machining parameters and the time to drill a single hole through a piece of square tube steel using a drill press. These values are calculated using equations (4) through (7). Therefore, as can be seen in Table 1, the machining time equals 0.0778 min or 4.67 seconds.

B) Experimental Drilling Time

An experiment was done to try and achieve an accurate machining time for drilling into angle iron and square tube steel. The same material was used in the experiment as was used to make the theoretical machining time estimations. A Central Machinery “Mini Vertical Milling/Drilling Machine” model 44991 was used for the experiment and can be seen in Figure 1. This drill press was used because this is the drill press that was available to the author in the lab and was used during the manufacturing of the rehabilitative gait machine. A 5/16 inch diameter HSS drill bit was used to drill the holes into the material. Cutting oil was also used during the experiment to lower the risk of damaging the tool and to make the drilling operation more efficient. A total of five trials were done each, for the angle iron and square tube steel. An average time in seconds was taken for each experiment. These times can be seen respectively for angle iron and square tube steel in Tables 2 and 3.

Figure 1. Central Machinery "Mini Vertical Milling/Drilling Machine

Table 2. Experimental Drilling Times for Angle Iron

Trial	**Time (sec)**	**Standard Deviation (sec)**
1	92	
2	120	
3	106	
4	91	
5	104	
Average	102.6	10.6

Table 3. Experimental Drilling Times for Tube Steel

Trial	**Time (sec)**	**Standard Deviation (sec)**
1	57	
2	59	
3	58	
4	63	
5	66	
Average	60.6	3.38

As can be seen in Table 2 the average time it took to drill one 5/16 inch hole into a piece of angle iron equals 102.6 seconds or 1.71 minutes. So the experimental machining time resulted in 102.6 $\pm$ 10.6 seconds.

As can be seen in Table 3, the average time it took to drill one 5/16 inch hole into a piece of square tube steel equals 60.6 seconds or 1.01 minutes. So the experimental machining time resulted in 60.6 $\pm$ 3.38 seconds.

When comparing the theoretical times with the experimental times it is clear to see that there is a large difference in time. The theoretical machining time for drilling angle iron is 2.39 seconds and the experimental machining time is 102.6 seconds. This corresponds to an error of 4192.9%. The theoretical machining time for drilling square tube steel is 4.67 seconds and the experimental machining time is 60.6 seconds. This corresponds to an error of 1197.6%. There are many reasons for this high of an error. First, the author is not an experienced drill press operator. The feed rate is determined manually by the operator and therefore was not constant and the feed rate was probably slower than what is expected for the cut. In addition, on the Central Machinery drill press there was not an accurate spindle speed setting. It was a dial which had a range of speeds but only the max and minimum settings were labeled. Therefore the spindle speed was not set correctly. The drill bit which was used during the experiment was not a new drill bit; therefore the bit was used and worn. For the theoretical calculations it is assumed that the drill bit used was not worn and could cut to its full potential.

This analysis or comparison shows that having the correct machining parameters will greatly reduce the machining time. If the experiment was run on an automatic drill press machine or by a professional machinist the correct feeds and speeds could have been set. In addition, if a drill bit which had minimal to no tool wear were used the drill cut would have been more effective. This would result in a faster and more efficient machining time and would greatly reduce the error.

3.3.2 Bandsawing

Before the machining time can be calculated for bandsawing, the tooth variable-pitch for the blade needs to be determined. This is done by first calculating the length of cut, which “is the distance that any tooth of the blade is in contact with the work as it passes through the cut” [20], and then using the tooth selection wheel chart found in [20] to determine the best blade pitch for the particular job. The length of cut for solid rectangular cross-section stock is the height of the cross-section. For a solid circular cross-section stock the length of cut is the diameter of the cross-section. The length of cut for angles, channels, I-beams, tubes, pipe, and hollow or irregular shapes is calculated by dividing the cross-sectional area of the cut by the distance the blade has to travel to finish the cut [20].

Once the length of cut is found and the blade pitch is determined it is time to determine the band speed (ft/min) which can be found in [20] for a given material. However, these band speeds found in [20] are for a bimetal bandsaw having a length of cut of 4 inches with coolant. So it is assumed that the material is being cut with a bimetal bandsaw blade. Therefore these band speeds need to be adjusted for different lengths of cut other than 4 inches [20].

- Increase speed by 15% for ¼” length of cut (10/14 blade)
- Increase speed by 12% for ¾” length of cut (6/10 blade)
- Increase speed by 10% for 1 ¼” length of cut (4/6 blade)
- Decrease speed by 12% for 8” length of cut (2/3 blade)

After the band speed has been found and adjusted if needed then the cutting rate (in^2/min) can be estimated from [20].

The time for machining, T_m, for bandsawing can be calculated using [20]:

$$T_m = \frac{A}{cutting\ rate} \tag{8}$$

where the cutting rate is measured in $in.^2$/min. “A” is the area of the cut, which is the cross-sectional area of the specific beam being cut [20].

A) Theoretical Sawing Time

Table 4. Theoretical Bandsaw Parameters

	Angle Iron	**Square Tube Steel**
Cross-sectional Area	0.297 in^2	0.422 in^2
Length of Cut	0.168 in	0.422 in
Variable-pitch Blade	10/14	8/12
Band Speed	270 fpm	300 fpm
Percent Adjustment	+ 15%	+ 12%
Adjusted Band Speed	311 fpm	336 fpm
Cutting Rate	3.5 in^2/min	3.75 in^2/min
Machining Time	0.085 min	0.113 min

i) Angle Iron

For all the calculations made it is assumed that a bi-metal bandsaw blade is being used to cut the material. Before the machining time to cut a piece of angle iron into two pieces can be calculated the length of cut first needs to be known. As mentioned earlier the length of cut of angle iron equals the cross-sectional area divided by the distance the blade has to travel to complete the cut. This is shown in the equation below:

$$L = \frac{A}{d} \tag{9}$$

where A is the cross-sectional area (in^2) and d is the distance the blade has to travel (in) to complete the cut. The cross-sectional area A for angle iron with equal side lengths can be calculated using the equation:

$$A = (2l - t)t \tag{10}$$

where l is the length (in) of the side or leg of the angle and t is the thickness (in). From the BOM in Appendix A the angle iron used had lengths of 1.25 inches and a thickness of 0.125 inches. From equation (10) the cross-sectional area, A, equals 0.297 in^2. Next is to find the distance, d, the blade travels. In order to find this distance, the way the angle iron is inserted into the vise needs to be known. Reference [23] stated an efficient way to load the angle iron into the vise. This can be seen in Figure 2.

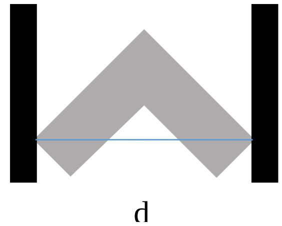

Figure 2. Angle Iron Loaded In a Vise

The distance of the cut, d, can be calculated using the Pythagorean Theorem which is represented in the following equation.

$$d = \sqrt{a^2 + b^2} \tag{11}$$

where a and b are the lengths of the angle iron, which equal 1.25 inches. Using equation 11, the distance of the cut, d, equals 1.77 inches. Now that the cross-sectional area and the distance of the cut have been found the length of cut can now be calculated. Using equation 9, the length of cut, L, equals 0.168 inches.

After the length of cut was found the tooth specification was determined for the blade from the tooth selection wheel in [20]. Next is to determine the band speed required to cut the given material. The angle iron is an ASTM A36 material. From [20], the band speed required to cut A36 steel is found. However, since the length of cut is not 4 inches the speed needs to be adjusted for the length of cut of the angle iron. Once the adjusted band speed is found the cutting rate is estimated from [20]. Now the machining time, T_m, can be calculated. The machining parameters and machining time for cutting angle iron using a band saw can be seen in Table 4. Therefore the machining time equals 0.085 minutes or 5.09 seconds.

ii) Square Tube Steel

As with the angle iron, it is assumed that a bi-metal bandsaw blade was used to cut the material for all cutting calculations. The length of cut for the square tube needs to be calculated which requires the cross-sectional area and distance of the cut. The cross-sectional area of square tube steel with equal side lengths was calculated using the equation:

$$A = 4t(l - t) \tag{12}$$

where t is the thickness (in) and l is the length of the sides (in) of the square tube steel. From the BOM in Appendices A and B, the square tube steel used was a 1" by 1" with a thickness of 0.12". Therefore using equation 12 the cross-sectional area, A, of the square tube steel used equals 0.422 in^2. The distance of the cut is equal to the width of the square tube steel which is equal to the length and equals 1 inch. Therefore using equation 9 the length of cut for the square tube steel equals 0.422 inches.

After the length of cut was found the tooth specification was determined for the blade from the tooth selection wheel in [20]. Next is to determine the band speed required to cut the given material. The square tube steel is an ASTM A500 material and according to [19] is a 1018 carbon steel. From [20], the band speed required to cut 1018 carbon steel is found. However, since the length of cut is not 4 inches the speed needs to be adjusted for the length of cut of the square tube steel. Once the adjusted band speed is found the cutting rate is estimated from [20]. Now the machining time, T_m, can be calculated. The machining parameters and machining time for cutting square tube steel using a band saw can be seen in Table 4. Therefore the machining time equals 0.113 minutes or 6.75 seconds.

B) Experimental Sawing Time

An experiment was done to try and achieve an accurate machining time for sawing into angle iron and square tube steel using a bandsaw. The same material was used in the experiment as was used to make the theoretical machining time estimations. The bandsaw used in this experiment was a Milwaukee 6230N Deep Cut Portable Bandsaw with Trigger Speed Control and can be seen in Figure 3. By the way it was used to cut the material, it can be considered a horizontal bandsaw. This saw was used because it was the saw available to the author in the lab and could have been used during the manufacture of the rehabilitative gait machine. Coolant was not used for sawing during the experiment. A total of five trials were done each, for the angle iron and square tube steel. An average time in seconds was taken for each experiment. These times can be seen respectively for angle iron and square tube steel in Tables 5 and 6.

Figure 3. Milwaukee 6230N Deep Cut Portable Bandsaw

Table 5. Experimental Sawing Times for Angle Iron

Trial	Time (sec)	Standard Deviation (sec)
1	19.29	
2	19.82	
3	19.36	
4	19.76	
5	21.68	
Average	19.98	0.87

Table 6. Experimental Sawing Times for Tube Steel

Trial	Time (sec)	Standard Deviation (sec)
1	10.66	
2	10.48	
3	10.25	
4	8.1	
5	8.16	
Average	9.53	1.15

As can be seen in Table 5, the average time to cut a single piece of angle iron into two pieces is 19.98 seconds or 0.333 minutes. Therefore the experimental machining time for cutting angle iron with a bandsaw is 19.98 ± 0.87 seconds.

As can be seen in Table 6, the average time to cut a single piece of square tube steel into two pieces is 9.53 seconds or 0.159 minutes. Therefore the experimental machining time for cutting angle iron with a bandsaw is 9.53 ± 1.15 seconds.

When comparing the experimental results with the theoretical machining times it can be seen that the experimental times are slower. The theoretical machining time for sawing angle iron equals 5.09 seconds and the experimental time equals 19.98 seconds. These times correspond to an error of 292.5%. The theoretical machining time for sawing square tube steel equals 6.75 seconds and the experimental time equals 9.53 seconds. These times correspond to an error of 41.2%. There can be a lot of factors which correspond to these high errors. First, the author is not an experienced bandsaw operator and machinist. This inexperience could result in incorrect and varying feed rates. In addition, since the Milwaukee bandsaw is trigger controlled the band speed is hard to determine resulting in incorrect band speeds. The trigger speed control ranges from 0 to 420 surface feet per minute. The blade used in the bandsaw was a cobalt XTL high performance bi-metal blade with tooth pitch of 14/18 teeth per inch. The blade was not changed for cutting the angle iron and square tube steel during the experiment. Therefore the correct blade tooth pitch was not used for sawing the angle iron and square tube steel. The blade being used in the bandsaw also had some signs of tool wear. Coolant was also not used during the experiment which resulted in a less effective and efficient operation.

This analysis shows that if all the parameters of the bandsaw operation were set correctly a faster and more efficient machining time could be achieved. If the experiment were run by an experienced or professional machinist a more efficient feed rate could have been set. If a different bandsaw were used, one that allows the operator to accurately set the band speed, and if coolant was used the sawing operation could have been more effective. In addition, if the correct blade types for the specific cuts were used and a blade with minimal to no tool wear were used, this would also have resulted in a more effective cut.

3.4 Cost Estimation

A cost estimation for manufacturing certain parts is wanted to show how machining extra parts can increase the total cost to produce a product. To perform cost estimations of machining different components the equation below was used [13 ch.25]:

$$C_c = C_o T_h + C_o T_m + \frac{C_o T_t}{n_p} + \frac{C_t}{n_p} \tag{13}$$

where C_c is the total cost per unit product. C_o is the cost rate, measured in \$/min, for the machine operator and the machine itself. T_h is the handling time or the time it takes for the operator to load, position, and unload the part into the machine. For the machining operations done in this study the handling time will include two times: first is the time to load and unload the part into the machine and second is the time it takes to position the part in place for the operation. This is done to provide a more specific penalty to drilling and sawing. From [24], a general time for loading and unloading a part into a machine, both a drill press and a band saw, is 30 seconds or 0.5 minutes. The time it takes to align a drill bit in place with the point of interest on the part using a drill press is 203 seconds or 3.38 minutes. The time it takes to align the band saw blade with the mark on the part is 11 seconds or 0.183 minutes. $\frac{C_o T_t}{n_p}$ is the cost of tool change time and $\frac{C_t}{n_p}$ is the tooling cost. These are going to be assumed as zero for this study. This is because the costs associated with the tool of the machine are dependent on the number of pieces machined by a specific tool. Since only one rehabilitation device per design was produced the number of machined pieces is minimal and tool change was assumed to have not happened. It is also unknown for certain cost estimations how many pieces can be machined from one tool. Therefore, cost associated with machine tools was viewed as unimportant for this study. The cost estimate equation becomes:

$$C_m = C_o T_h + C_o T_m \tag{14}$$

where C_m is the cost per machining operation.

The cost estimate for the theoretical and experimental drilling and sawing times can be seen in Table 7. Equation (14) was used to calculate the cost estimates. As mentioned above, the handling time per cut for drilling is 3.88 min and the handling time per cut is for sawing is 0.683 minutes. The cost rate is $58/hr. This is the cost rate for the machine shop at the University of Nebraska-Lincoln College of Engineering. This cost rate was picked because it is a known realistic cost rate for a machine shop and it is the machine shop which manufactured parts for the production of both iterations of the rehabilitative gait machine. The theoretical and experimental machining times were provided by Tables 1 through 6. The data in Table 7 shows the cost which is incurred from just machining the material once for one hole or one cut. It doesn't provide the total cost per unit product because tooling factors are ignored.

Table 7. Theoretical and Experimental Cost Estimates

	Drilling		Sawing	
	Angle Iron	Tube Steel	Angle Iron	Tube Steel
Theoretical Cost	\$3.79	\$4.50	\$0.74	\$0.77
Experimental Cost	\$5.40	\$4.73	\$0.98	\$0.81

3.5 Conclusion

The theoretical and experimental values for drilling and sawing in this study provide lower and upper bounds on estimates of cost in realistic scenarios. From this analysis it can be seen that having an inexperienced operator machine parts can greatly increase the machining time. This increase in machining time results in an increase in machining cost. However, this experiment does show realistic problems in creating products in a lab or at-home setting. For this project quick machining, such as cutting some angle iron to length or drilling holes in material so that they may be joined together, was done in a lab setting with small-scale machining equipment. The machining was done by an amateur or inexperienced machinist. Even though we didn't have to pay professional machinist shop rates, these quick machining operations can still incur additional cost. The additional cost can come from buying new tools, such as drill bits and saw blades, because the correct feeds and speeds were not followed by an inexperienced operator. Therefore it is important to use the correct machining parameters because it can reduce the machining time, reduce the tool wear, reduce the machining cost, and overall make the machining process more effective and efficient.

In addition, the drilling/sawing experiments could have been improved by doing more trials to get a better data trend. A statistical analysis could then be made to find the statistically adequate number of trials that can be done for the experiment. In addition, if a large number of operators were to run the same experiment, a larger data set could be achieved. This data set could then be analyzed and a better machining time average can be found. Moreover, if drill bits and blades that were not used or worn would have been used during the experiment and if the correct blade types were used for sawing the angle iron and tube steel, better experimental results could have been found.

CHAPTER 4 – DFM ANALYSIS

As previously mentioned, the goal of this project is to show how implementing DFM and DFA into a product design process can reduce the cost and make the process more efficient. In this chapter the first design of the rehabilitative pediatric gait machine is evaluated and analyzed through the use of DFM. Even though the rehabilitative machine has already been produced, the hope of this analysis to prove that if these techniques were used during the design of the product the design could have been improved lowering the cost to produce the product. An in-depth analysis is performed on the rail, foot pedal, and rocker sub-assemblies and the cams to better show how DFM can improve products. Cost estimations will be calculated for the machining of the rail, foot pedal, rocker sub-assemblies and the cams to compare differences between the two designs and to show how the decisions made related to manufacturing method affect the cost.

Specific guidelines and rules for DFM are listed in the background/literature review chapter of this paper. These guidelines do not have to be followed religiously but are a good guide when first designing a product. Following these guidelines helps the designer to create an efficient design. In this section the device will be analyzed to show how the designer may or may not have considered DFM while designing the device.

Table 8. DFM Guidelines Followed

DFM Guidelines:	**Design 1**	**Design 2**
Reduce Number of Parts		x
Use Standardized Components	x	x
Use Common Parts Across Product Lines	x	x
Multifunctional Parts		
Ease of Fabrication	x	x
Loose Tolerances	x	x
Avoid Secondary Operations	x	x
Good Use of Processes' Special Characteristics		

From Table 8, it can be seen that overall both designs use commercially standardized parts that are easy to fabricate or machine. The machine in both designs is largely built up using 1.25” by 1.25” by 0.125” thick angle iron and 1” by 1” by 0.12” thick square tube steel. These products are commercially available (for this project from McMaster-Carr) and were ordered in bulk so as to keep the cost down. In addition, other materials were used to construct both machines, but angle iron and square tube steel were a large portion and are a main focus of this analysis. This can be seen in the BOM in Appendices A and B. The angle iron and square tube steel are low carbon steels which are made for easy fabrication. This ease of fabrication lowers the cost. For most of the construction the fabrication or machining operations used for the angle iron and tube steel included cutting the material to length and drilling holes into it so that different pieces could be joined together through the use of fasteners. These are quick and easy machining operations that are relatively cheap. Wood was used to construct the frame of the machine in both designs. Wood has certain advantages for frame construction because wood can be easily machined and joined and is commercially standardized and available. It is also lighter and cost less than if the frame were constructed out of steel. The angle iron, square tube steel, and wood components required no secondary operations either. Loose tolerances were used for both designs because the goal was to design a rehabilitative gait machine that produced a proper gait path, not the precision of the product.

The second design reduced the number of parts from design one. This will be addressed more in the DFA chapter. Since only one machine was built from design one it was not possible to use common parts across product lines for multiple products. However, common parts were used between the constructions of both machine designs. If multiple machines of both designs were produced then there would be common parts used across product lines. So, for this study it will be considered that both designs used common parts across product lines.

4.1 Design 1

Multiple parts and sub-assemblies had to be machined for the first design of the rehabilitation machine. Of these sub-assemblies and parts were the rails, foot pedals, rockers and cams. These sub-assemblies and cams are essential for an effective and operable machine. These sub-assemblies and cams, as compared to other parts of the machine, required a lot of machining before they could be assembled. An analysis was made to show how machining these sub-assemblies and cams adds cost to the design of a product, and if these costs were known earlier in the design they might warrant a redesign. In the following figures are pictures of the rails, foot pedals, rockers and cams of Design 1.

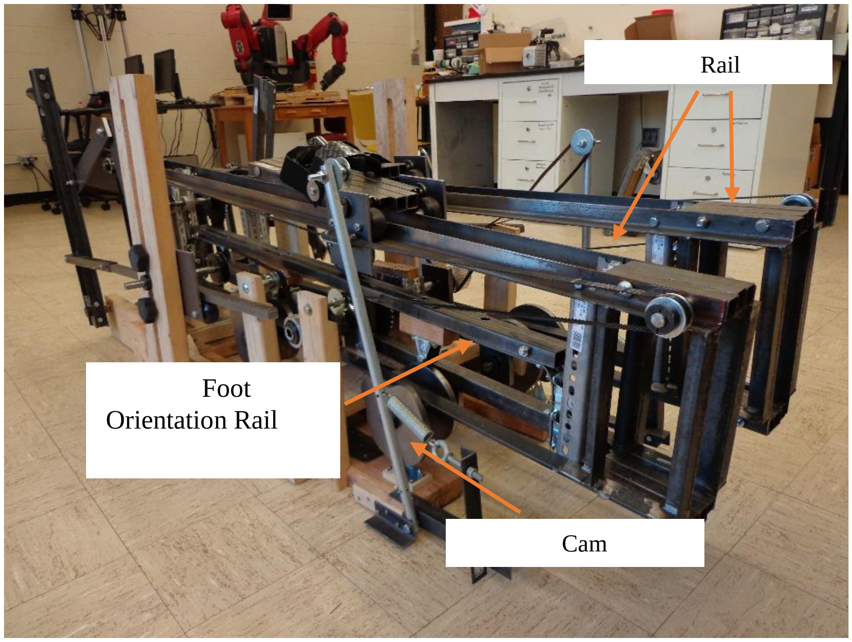

Figure 4. Design 1 Rail Sub-Assemblies and Cams

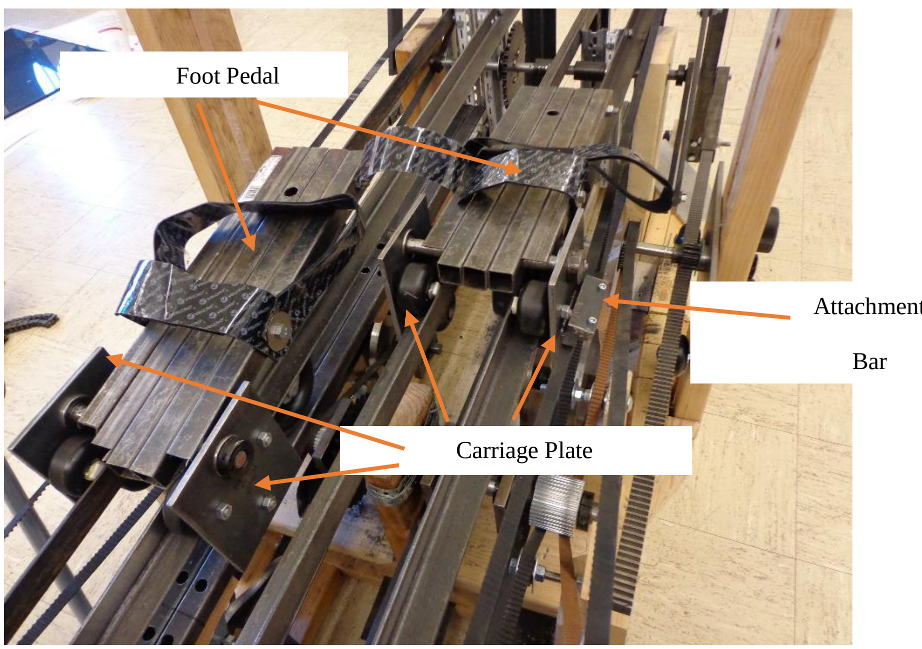

Figure 5. Design 1 Foot Pedal Sub-Assemblies

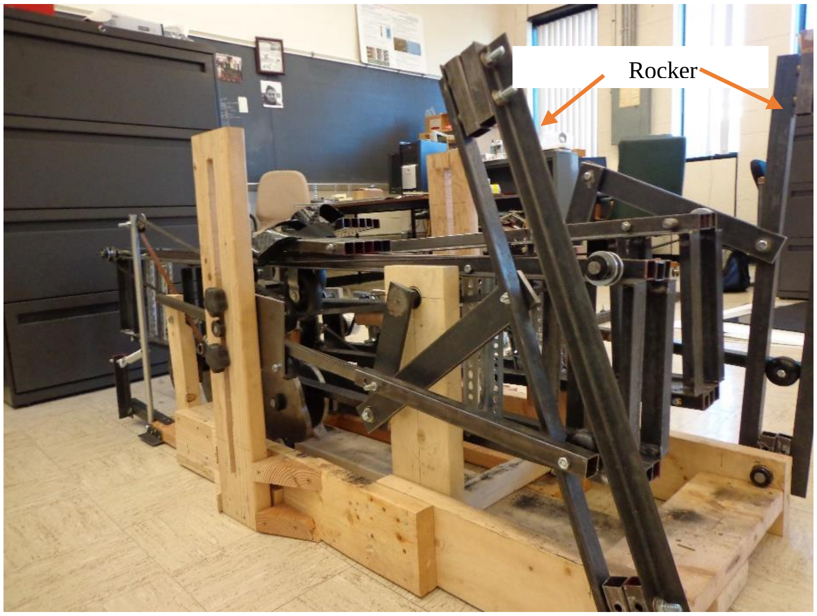

Figure 6. Design 1 Rocker Sub-Assemblies

Cost estimations for the machining of these sub-assemblies and cams was made using equation (14) from Chapter 3. The cost rate for these cost estimations is $58/hour. This was the cost rate of the UNL College of Engineering machine shop at the time of the production of the first rehabilitation machine design. The handling time T_h is considered to be the time it takes for the operator to load, position, and unload the part into the machine. Drilling and sawing were the primary machining operations used to manufacture these sub-assemblies. As previously mentioned in Chapter 3, the time to load and unload a part into a machine is 0.5 minutes, the time to position a drill press is 3.38 minutes, and the time to position a part with the saw blade is 0.168 minutes. However, if there are two hole locations close enough to each other that the part did not need to be unloaded and reloaded back into the drill press before the next hole needed to be located and drilled, the drill is just repositioned to the next hole location. After being repositioned and drilled then the part is unloaded. This results in a handling time of 0.5 minutes for loading and unloading once and 6.76 minutes for positioning the drill twice.

Equations (4-12) from Chapter 3 were used to calculate the theoretical drilling and sawing times. Theoretical machining times are used because they provide a more desirable and consistent machining time. The theoretical machining times for drilling and cutting the parts required to construct the rails, foot pedals, and rockers are presented in Table 9.

Table 9. Theoretical Machining Times for Design 1

	Angle Iron		Square Tube Steel		Slotted Angle Iron	5/8 Shaft	P3 Bracket	P4 Bracket	Carriage Plate	Attachment Bar
Drilling Time (minutes)	3/8" - 0.043	5/8" - 0.057	3/8" - 0.064	5/8" - 0.078			0.181	0.162	0.242	
Sawing Time (minutes)	0.085		0.113		0.031	0.102	1	0.97	0.662	0.271

The machining times presented in Table 9 are the times to machine one single part. For the angle iron and square tube steel the time listed is the time to make one cut or drill one hole at 3/8" or 5/8" diameter. There are multiple holes drilled in the angle iron and square tube steel at these diameters in order to construct the sub-assemblies. The P3 bracket is a 3.5" by 3.5" steel plate with thickness of 0.5" and a 2" diameter hole drilled into it. The P4 bracket is a 3.125" by 3.625" steel plate with thickness of 0.5" and a 1.625" hole drilled into it. There are a total of four P3 brackets and eight P4 brackets, two P3s and four P4s per rail, used in the construction of the two rails on the machine. A picture showing how the brackets are attached to the rail can be seen in Figure 7. The carriage plate is a 4.565" by 5.245" steel plate with thickness of 0.25". Each carriage plate has a total of 4 holes drilled into it. One hole is 0.625" in diameter and the other three are 0.315" in diameter. There are a total of four carriage plates, two per foot pedal, used in the construction of the foot pedals. The attachment bar is a 1" by 3" steel bar with thickness of 0.25". There a total of two of them and each one is welded to the carriage plates and is used to attach the pulley belts to the foot pedal. The carriage plate and attachment bar can be seen in Figure 5. The 5/8" shaft is made from 1566 steel [19]. However, in order to use the process outlined in Chapter 3, the cutting speed for the shaft will be the speed required to cut 1541 steel [20]. According to [25], 1541 steel is comparable to 1566 steel.

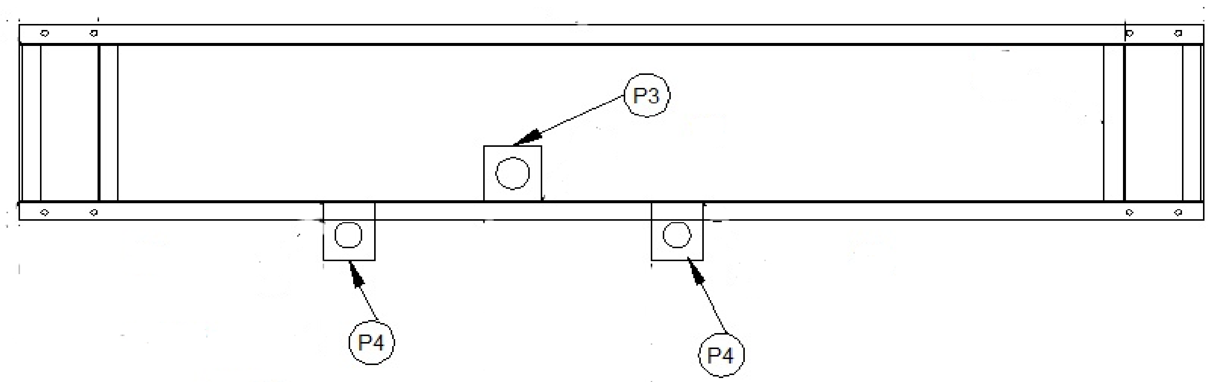

Figure 7. Angle Iron Frame with P3 and P4 Brackets

The machining times in Table 9 were used to calculate the machining cost estimations. The following tables show the cost estimations for cutting and drilling various materials to construct the rails, foot pedals, and rockers. Tables 11-13 show the cost to machine the material used for the two rail sub-assemblies, the two foot pedal sub-assemblies, and the two rocker sub-assemblies. Table 14 shows the total material cost to manufacture the rail, foot pedal, rocker sub-assemblies and the cams for each design and the percent change between Design 1 and Design 2. The plus sign means there was a percent increase and the minus means there was a percent reduction. This does not include the cost of the fasteners required to assemble the sub-assemblies together or to other parts. All of the material required to manufacture and assemble the rehabilitative machine for Design 1 and Design 2 can be found in the BOM in Appendices A and B.

As an example for how these cost estimations were done the machining time and cost estimation will be shown for drilling one 0.625” hole and three 0.315 hole in a carriage plate. Table 10 shows the machining parameters used for drilling and cutting the carriage plates. The steel used for the carriage plates is a low carbon steel which meets ASTM A108 specifications and has a Rockwell hardness value of B70 [19]. From [26], Rockwell hardness value of B70 corresponds to a Brinell hardness value of 121. Since the steel is a low carbon steel it will be assumed that it is 1018 steel with Brinell hardness of 121. From [20], the cutting speed of a 1018 carbon steel having Brinell hardness values ranging from 100-125 is 100 feet per minute (fpm) or 1200 in./min. So the cutting speed, v, for drilling into the carriage plates equals 1200 in./min. This cutting speed is used to calculate the spindle speed, using equation (7) from Chapter 3, once a bit diameter is specified.

The drill bits used for cutting the material are assumed to be HSS twist drill bits with tip angles equaling 118°. Holes with diameters of 0.625” and 0.315” are to be drilled into the plate which has a thickness of 0.25”. Using the general rule stated in [21], the feed for 0.625” drill bit is 0.01 in./rev and the feed for 0.3125” (which is close to 5/16”) is 0.005 in./rev. These feeds and the corresponding spindle speeds are then used to calculate the feed rate using equation (6) from Chapter 3. After using equation (5), from Chapter 3, to find the approach distance the machining time can be calculated using equation (4) from Chapter 3. These machining parameters and the machining time to make one cut can be seen in Table 10.

Using equation (14) in Chapter 3, the estimated cost to drill one 0.625” hole and three 0.315” hole in a carriage plate is calculated. As mentioned earlier, the cost rate is

$58/hr. For the one 0.625" hole the handling time is 3.88-min (0.5-min for loading/unloading and 3.38-min for positioning) and the machining time is 0.072-min. After converting the cost rate to minutes, the cost to machine one 0.625" hole in a carriage plate is $3.82. Since the three 0.315" holes are close enough to each other that the plate does not need to be unloaded from the drill press for each hole, the handling time equals 10.64-min (0.5-min for loading/unloading and three times 3.38-min or 10.14-min for position for all three holes). The machining time is 0.171-min (the time to machine one hole, 0.057-min, times 3). The cost to machine these three holes is $10.45. Therefore, the drilling cost for one carriage plate is $14.27. In addition, the drilling cost for all four carriage plates is $57.08, which can be seen in Table 12.

Table 10. Parameters for Machining Carriage Plates

	Drilling		**Sawing**		
	0.625"	0.315"	4.565"	5.245"	
Cutting Speed (in/min)	1200	1200	0.25	0.25	**Length of Cut (in)**
Spindle Speed (rev/min)	611	1213	10/14	10/14	**Variable-pitch Blade**
Feed Rate (in/min)	6.11	6.07	300	300	**Band Speed (fpm)**
Approach Distance (in)	0.188	0.095	+ 15%	+ 15%	**Percent Adjustment**
			345	345	**Adjusted Band Speed (fpm)**
			1.14	1.31	**Cross-sectional Area (in^2)**
			3.7	3.7	**Cutting Rate (in^2/min)**
Machining Time (min)	0.072	0.057	0.308	0.354	

Table 11. Total Machining Cost for Design 1 Rail Sub-Assemblies

	Cost to Cut	Cost to Drill	Sub-Total
Angle Iron	$11.84	$170.57	$182.41
Tube Steel	$21.56	$238.32	$259.88
Slotted Angle Iron	$5.52		$5.52
Shafts	$3.04		$3.04
P3 Bracket	$9.12	$15.72	$24.84
P4 Bracket	$18.08	$31.28	$49.36
Total			$525.05

Table 12. Total Machining Cost for Design 1 Foot Pedal Sub-Assemblies

	Cost to Cut	Cost to Drill	Sub-Total
Tube Steel	$7.70	$117.36	$125.06
Carriage Plates	$7.84	$57.08	$64.92
Shafts	$1.52		$1.52
Attachment Bar	$3.18		$3.18
Total			$194.68

Table 13. Total Machining Cost for Design 1 Rocker Sub-Assemblies

	Cost to Cut	Cost to Drill	Sub-Total
Angle Iron	$2.96	$64.38	$67.34
Square Tube Steel	$6.16	$64.78	$70.94
Total			$138.28

Table 14. Material Cost of Sub-Assemblies and Total

	Design 1	Design 2	Percent Change
Rail	$427.89	$660.00	+54.2%
Foot Pedal	$164.85	$566.44	+243.6%
Rocker	$45.54	$45.54	0%
Cams	$805.64	$85.46	-89.4%
Total	$1443.92	$1357.44	-5.99%

4.1.1 Rail

The rail subassemblies for the first design are constructed mostly of angle iron and square tube steel. The angle iron and square tube steel are built into a frame which acts as a rail for the foot pedals. As mentioned before, the angle iron and steel tube used are commercially standardized and available. They are relatively easy to machine. Since they were used in abundance they could be ordered in bulk to save money. From McMaster-Carr, the angle iron and square tube steel can be ordered in lengths of 6 feet (72-inches). To construct one rail frame, four 72-inch long pieces and eight 9.9375-inch long pieces of angle iron were needed. This meant that eight cuts each at 9.9375-inches need to be machined. In addition, twenty 3/8” holes and four 5/8” holes per rail were drilled into the angle iron.

Twelve 6-inch pieces of square tube steel were used in the construction of one rail. Therefore, twelve cuts each at 6 inches need to be machined per rail. Two cuts at 60 inches long of square tube steel are used to build the foot orientation rail, which can be seen in Figure 4. In addition, twenty-six 3/8” holes and six 5/8” holes per rail were drilled into the square tube steel.

In addition to machining multiple cuts of angle iron and square tube steel, other material had to be machined in ordered to completely manufacture the rails. As mentioned earlier, there are two P3 brackets and four P4 brackets per rail that were machined. A 5/8” diameter shaft was cut into two 6 inch rods per rail which were used to help assemble the rail. Zinc plated slotted angle iron was cut into four 9.9375 inch pieces per rail which were used as a guide for the foot orientation rail. The cost of machining the two rail sub-assemblies can be seen in Table 11 and the material cost can be seen in

Table 14. The estimated total cost to manufacture the rail sub-assemblies of Design 1 is $952.94.

4.1.2 Foot Pedal

Similar to the rail sub-assemblies, the foot-pedal sub-assemblies were also constructed primarily out of square tube steel. The components which make up the foot pedal can be seen in Figure 5. A single foot pedal is composed of five 12-inch pieces of square tube steel and two carriage plates. In addition to cutting the tube steel to length, ten 3/8" holes and six 5/8" holes per foot pedal had to be drilled into the square tube steel. The outside carriage plate also has an attachment bar welded to it so that the pulley belts can attach to the foot pedal. A 5/8" shaft is used to join the carriage plates and square tube steel. Each pedal also includes six 54-mm diameter skateboard wheels and a 5" rigid thermoplasticized rubber caster. The cost of machining the two foot pedal sub-assemblies can be seen in Table 12 and the material cost can be seen in Table 14. The estimated total cost to manufacture the foot pedal sub-assemblies of Design 1 is $359.53.

4.1.3 Rocker

The rocker sub-assemblies were constructed of angle iron and square tube steel joined together by fasteners. The rocker sub-assemblies can be seen in Figure 6. Two 3-foot pieces of angle iron and four 4-inch pieces of square tube steel per rocker were machined to produce the rocker. In addition to cutting the material to length, nine 3/8" holes had to be drilled into the angle iron and eight 3/8" holes and one 5/8" hole had to be drilled into the square tube steel per rocker. The cost of machining the two rocker sub-assemblies can be seen in Table 13 and the material cost can be seen in Table 14. The estimated total cost to manufacture the rocker sub-assemblies of Design 1 is $183.82.

4.1.4 Cams

There are eight cams machined for Design 1. A cam can be seen in Figure 5. The cams were machined out of four 18" by 18" by 0.5" thick A36 steel plates. The steel plates are commercially available as they were ordered from McMaster-Carr [19]. The material cost of the cams can be seen in Table 14. However, they were not easy to fabricate. The cams had to be machined (by University of Nebraska-Lincoln College of Engineering Machine Shop) specifically to a certain shape. The machining time for one cam is about 3 hours. This includes the handling time and machining time. Using equation (13) from Chapter 3, the total cost per cam equals $174. This was calculated by using the University of Nebraska-Lincoln College of Engineering Machine Shop rate which was $58/hour. Since eight cams were manufactured for this design, the total cost to machine all the cams equals $1392. Adding the material cost to the total machining cost gives a total cost of $2197.64.

4.2 Design 2

The second design of the rehabilitative gait machine was redesigned to create a better and more effective machine. Similar to Design 1, a lot of parts and sub-assemblies for the rehabilitative gait machine had to be machined for the construction of the machine. However, through the use of DFM concepts the rail, foot pedal, and rocker sub-assemblies were redesigned. In addition, because of these redesigns the cams were also redesigned. These redesigns of the rail, foot pedal, and rocker sub-assemblies and the cams can be seen in the following figures.

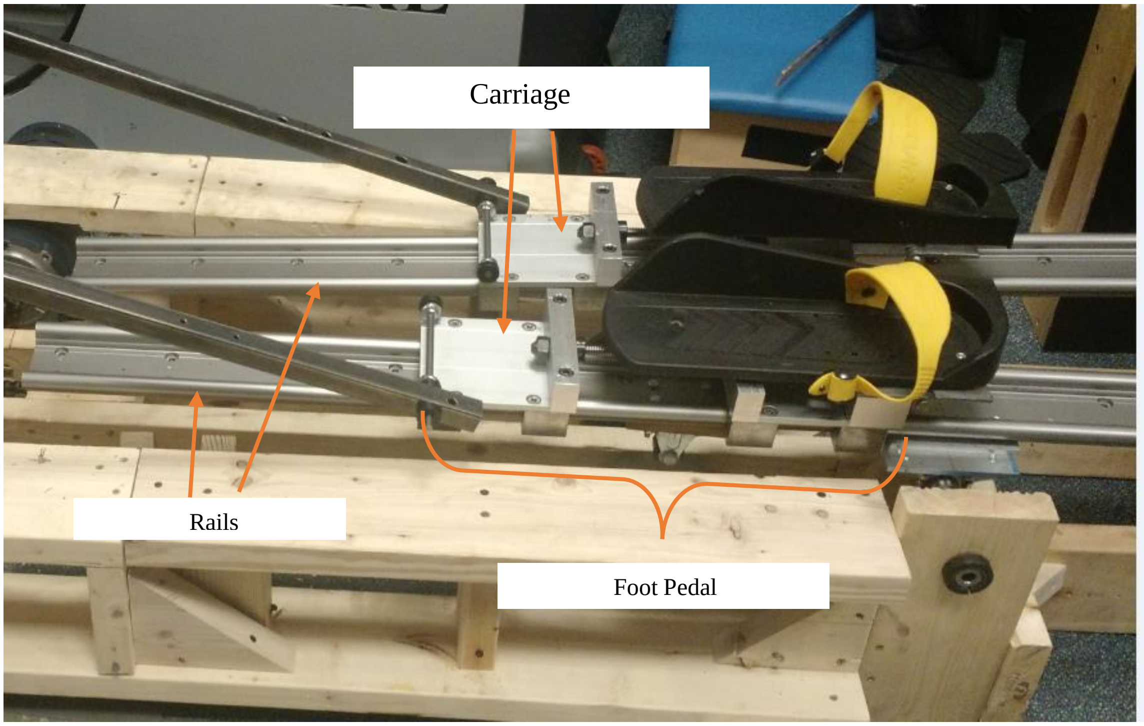

Figure 8. Design 2 Rail and Foot Pedal Sub-Assemblies

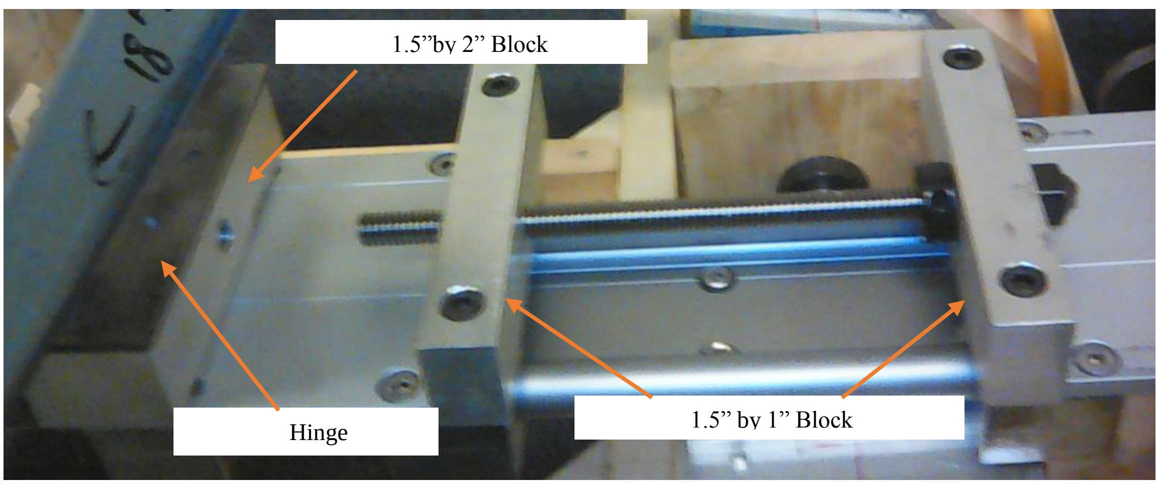

Figure 9. Design 2 Foot Pedal Sub-Assembly (Close-Up)

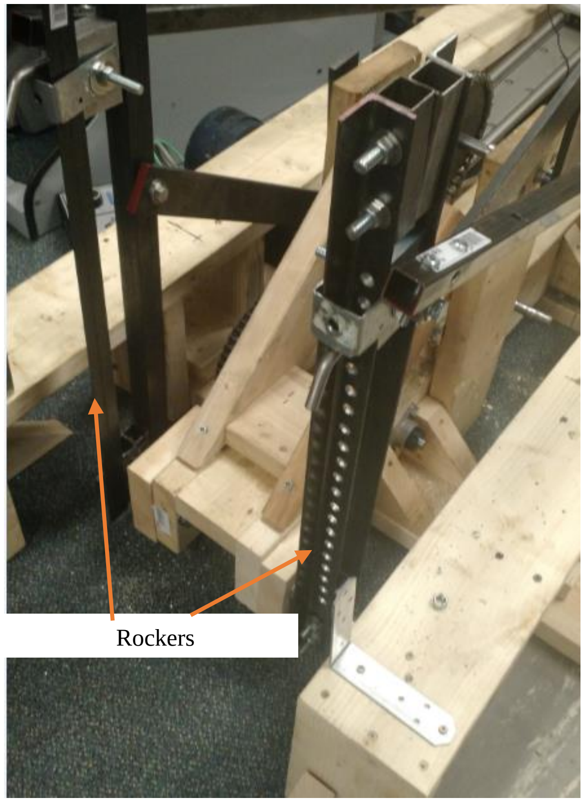

Figure 10. Design 2 Rocker Sub-Assemblies

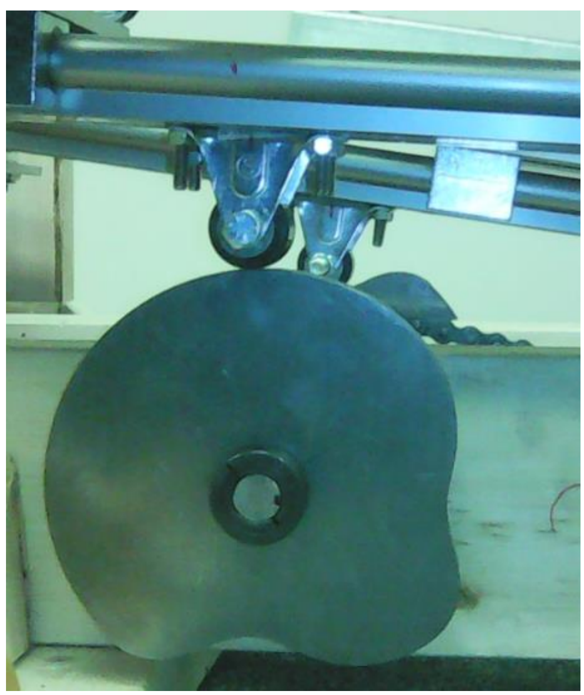

Figure 11. Cam in Design 2

Cost estimations for the machining of these sub-assemblies and cams was made using equation (14) from Chapter 3. As mentioned earlier, the cost rate for these cost estimations is $58/hour. The handling time T_h is considered to be the time it takes for the operator to load, position, and unload the part into the machine. Drilling and sawing were the primary machining operations used to manufacture these sub-assemblies. The same time to load and unload a part into a machine and the time to position a drill press and to position a part with the saw blade used for Design 1 will be used for Design 2. Equations (4-12) from Chapter 3 were used to calculate the theoretical drilling and sawing times. Theoretical machining times are used because they provide a more desirable and consistent machining time. The theoretical machining times for drilling and cutting the parts required to construct the rails, foot pedals, and rockers are presented in Table 15.

Table 15. Theoretical Machining Times for Design 2

	Angle Iron	Square Tube Steel		1" by 1.5" Aluminum		2" by 1.5" Aluminum		5/8" Shaft	Hinge
Drilling Time (minutes)	3/8" - 0.043	3/8" - 0.064	5/8" - 0.078	8 mm - 0.066	0.5" - 0.047	8mm - 0.066	0.5" - 0.088		0.037
Sawing Time (minutes)	0.085	0.113		0.107		0.214		0.102	

The machining times presented in Table 15 are the times to machine one single part. For the angle iron and square tube steel, the time listed is the time to make one cut or drill one hole at 3/8" or 5/8" diameter. Multiple holes at these diameters were drilled in order to manufacture the rocker sub-assemblies. The 5/8" shaft is made from 1566 steel [19]. However, in order to use the process outlined in Chapter 3, the cutting speed for the shaft will be the speed required to cut 1541 steel [20]. According to [25], 1541 steel is comparable to 1566 steel. The hinge is assumed to be made of 1018 steel with Brinell hardness of 100-125 so that the process outlined in Chapter 3 for drilling can be followed.

McMaster-Carr, the distributor of the hinge, did not provide information for what type of steel the hinge was made of.

4.2.1 Rail

It can easily be noticed that the rail in design 1 is made primarily of angle iron and square tube steel throughout. Using the DFM guideline of reducing parts, the angle iron and square tube steel parts in the first design do not meet all the criteria for a part to be separate. All the angle iron parts are made from the same low carbon ASTM A36 steel and all the square tube steel parts are made from the same low carbon ASTM A500 steel. There is no reason why the angle iron and square tube steel parts need to be a different material. Therefore all these parts can theoretically be combined. This inspired the redesign of the rails into the rails which are now being used for design 2. The rails for the second design can be seen in Figure 8. The rail, which is a commercially available component, is made of anodized aluminum and is 74 mm wide and 1500 mm long. The cost of one rail is $330.00. Therefore the total material cost of the rails in design 2 is $660.00 [19]. This can be seen in Table 14.

4.2.2 Foot Pedal

The foot pedals needed to be redesigned because of the redesign of the rails. The new rails, which are special standardized parts, can only be used with matching carriages. The carriages are made of anodized aluminum and use sleeve bearings to handle conditions, such as dirt, water, impact and vibration. Each carriage also includes four mounting holes 38-mm deep with an M8 thread size and thread pitch of 1.25-mm. Four total carriages were used, two for each foot pedal. Each carriage cost $113.08 and therefore the carriages used for the foot pedals cost $452.32 [19]. This carriage cost is included in the material cost seen in Table 14 for the foot pedal of Design 2. The other materials included in the cost in Table 14 are aluminum blocks, hinges, and a foot rest which were used to construct the foot pedals. Two 6-inch long by 1.5” by 2” aluminum blocks had to be cut from a 1-foot long stock. Two 8-mm diameter holes and one 0.5-inch diameter hole had to be drilled into each block. Four 6” long by 1.5” by 1” aluminum blocks had to be cut from a 2-foot long stock. Two 8-mm diameter holes and one 0.5-inch diameter hole had to be drilled into each block. Two hinges, one for each foot pedal, each had four 3/8” holes drilled into them. The cost to machine the aluminum blocks and the hinges can be seen in Table 16. The table shows the total cost for all the machining done on the six aluminum blocks and the two hinges. Therefore, the estimated total cost to manufacture the foot pedal sub-assemblies in Design 2 is $665.35. The foot pedals can be seen in Figures 8 and 9.

Table 16. Total Machining Cost for Design 2 Foot Pedal Sub-Assemblies

	Cost to Cut	**Cost to Drill**	**Sub-Total**
1" Aluminum Block	$3.04	$43.80	$46.84
2" Aluminum Block	$1.74	$21.97	$23.71
Hinge		$28.36	$28.36
Total			$98.91

4.2.3 Rocker

The same rockers used in Design 1 were used in Design 2. However, because of the redesign some additional machining was done to the rockers. Holes were drilled into the angle iron so that the rehabilitative gait machine could be adjustable for different stride lengths. Twenty 3/8” diameter holes were drilled into one angle iron side of each rocker. The cost to machine the angle iron and square tube steel for the Design 2 rockers can be seen in Table 17 and the material cost can be seen in Table 14. Therefore, the estimated total cost to manufacture the rocker sub-assemblies in Design 2 is $199.52. The rockers can be seen in Figure 10.

Table 17. Total Machining Cost for Design 2 Rocker Sub-Assemblies

	Cost to Cut	**Cost to Drill**	**Sub-Total**
Angle Iron	$2.96	$80.08	$83.04
Square Tube Steel	$6.16	$64.78	$70.94
Total			$153.98

4.2.4 Cams

The cams for Design 1 were redesigned to decrease the number of cams being manufactured for the machine. After redesigning, the number of cams was decreased to two. This greatly reduced the cost of manufacturing Design 2. Two Cams were machined out of an 8” by 12” by 0.5” thick A36 steel plate. This plate was commercially available from McMaster-Carr [19]. The material cost for the cams can be seen in Table 14. However, they were not easy to fabricate. The cams had to be machined (by University of Nebraska-Lincoln College of Engineering Machine Shop) specifically to a certain shape. The machining time for one cam is about 3 hours. This includes the handling time and machining time. Using equation 13 the total cost per cam equals $174. This was calculated by using the University of Nebraska-Lincoln College of Engineering Machine Shop rate which was $58/hour. Since two cams were manufactured for this design the total cost to machine all the cams equals $348. Adding the material cost to the total machining cost gives a total cost of $433.46. Figure 11 shows one of the cams used in Design 2.

4.3 Discussion

The data presented in this chapter help to show how using DFM techniques early in the design process can help reduce cost and eliminate the need for redesign. This is being done by analyzing the cost to manufacture two different designs of a rehabilitative gait machine. The second design is a redesign of the first. The three main sub-assemblies and the cams of both machines were analyzed and are compared to show that if DFM was used during the design stage of Design 1 then the redesign or Design 2 would have been done during this stage and money wouldn't have been spent to construct Design 1. The cost to manufacture the rail, foot pedal, and rocker sub-assemblies, cams, and their sum for both designs can be seen in Table 19. The redesign of Design 1 resulted in a 47% reduction in manufacturing cost. This proves that the DFM techniques could have reduced the cost if they were used effectively during the design stage of the first design. As can be seen in Table 19, there was a reduction in cost to manufacture the rails and the cams and there was an increase in cost to manufacture the foot pedals and rockers. Even though there was not a reduction in cost for all the sub-assemblies, the reductions made were significant enough to reduce the total cost. Notably, the redesign of the cams reduced the cost significantly. The cams had the highest reduction in both material and machining cost which resulted in the highest reduction in overall manufacturing cost.

The increases in cost can be greatly attributed to the redesign of specific parts. Redesigning the rail caused an increase in the foot pedal cost because only specific carriages can be used with the rails. The penalty of cost primarily comes from the specifically designed carriages. In addition, aluminum was machined so that a foot pedal could be built upon the carriages. Therefore, the foot pedals were not made of only angle iron and square tube steel which was cheap to buy in bulk. However, the number of parts was reduced for the foot pedals which reduced machining time and cost. Two carriages per foot pedal were also used to make the machine adjustable for different stride lengths. The rocker sub-assembly was also more expensive to manufacture for the second design. However, as mentioned earlier, this is because additional machining had to be done in order to make the machine adjustable for different stride lengths.

For this study, reducing the number of parts had the most influence in reducing cost. Decreasing the number of parts not only decreases the amount of material in a sub-assembly but it also decreases the amount of machining done for that sub-assembly, thereby, reducing the machining cost. This can be seen in Table 18. The reduction in machining cost from Design 1 to Design 2 for these sub-assemblies and cams is 73.3%. The reduction in material cost for these sub-assemblies and cams is 5.99%. Even though there was a 54.2% increase for the material cost of the rails there was significant reduction of 100% in machining cost. This led to a 30.7% reduction in overall manufacturing cost of the rails. This shows that reducing the machining that needs to be done on a product, regardless of what operation or material, plays a significant role in cost reduction. For this study, machining played more of an importance in cost reduction than the material used. This shows that when designing a product it is important to pay attention to how much machining has to be done in order to produce a product. This study also shows that there is more room for improvements in machining than the raw material to reduce cost. This is the purpose of DFM. DFM helps a designer to evaluate and analyze the design so that any additional penalties from having too many parts to machine and complex machining can be avoided. It gives the designer an effective way to find the minimal amount of machining that needs to be done to their product in order to manufacture and assemble it. This can be best seen between the rails and cams of both designs.

Table 18. Machining Cost of Sub-Assemblies and Total

	Design 1	**Design 2**	**Percent Change**
Rail	$525.05		-100%
Foot Pedal	$194.68	$98.91	-49.2%
Rocker	$138.28	$153.98	+11.4%
Cam	$1392	$348	-75%
Total	$2250.01	$600.89	-73.3%

Table 19. Manufacturing Cost of Sub-Assemblies and Total

	Design 1	**Design 2**	**Percent Change**
Rail	$952.94	$660.00	-30.7%
Foot Pedal	$359.53	$665.35	+85.1%
Rocker	$183.82	$199.52	+8.5%
Cam	$2,197.64	$433.46	-80.3%
Total	$3693.93	$1,958.33	-47%

For these main sub-assemblies and the cams, the redesign using DFM guidelines proved to be effective in reducing the cost to manufacture. This shows that if the DFM guidelines would have been used early on in the design process the machine could have been manufactured more efficiently and effectively. The redesign also helped reduce the bulkiness of the first design and made it more ergonomic.

CHAPTER 5 – DFA ANALYSIS

As previously mentioned, the goal of this study is to show how implementing DFM and DFA into the design of a rehabilitative gait machine can reduce the cost and make the process more efficient. In this chapter the first and second design of a rehabilitative pediatric gait machine is evaluated and analyzed through the use of DFA. DFA is a technique or set of guidelines that helps a product to be assembled efficiently. DFA guidelines are presented and outlined in Chapter 2. A DFA table is used to perform an analysis of the DFA guidelines and presents penalties for how a part is assembled into the product in response to violations of those guidelines [10]. An assembly index and assembly times for various operations are the penalties presented in a DFA table. The assembly index represents the penalties associated with how the part is retrieved, handled and inserted. The higher the assembly index the more difficult it is to assemble that part. Therefore, the assembly index represents the difficulty to assembly a part and is a way to measure that difficulty. The times for the different assembly operations in the DFA tables are provided in [24]. These are estimated times for similar assembly operations used in the construction of the machine, as opposed to the exact times to do the specific operations used to assemble the machine. The primary goal of DFA is to reduce assembly cost and improve product quality, and it has been found that reduction of parts is one important aspect of this. This is shown in the DFA tables. These DFA tables were produced for both designs of the machine and can be seen in Appendices C and D. However, in this chapter an in-depth analysis will be performed on the rail, foot pedal and rocker sub-assemblies to show how DFA can improve a product and make its assembly more efficient.

5.1 Design 1

The first design of the rehabilitative machine has multiple parts and sub-assemblies which were assembled to produce the final product. Of these sub-assemblies, the most essential for an effective and operable machine are the rail, foot pedal, and rocker sub-assemblies. Multiple parts are used to construct each of these sub-assemblies. An analysis is performed on each sub-assembly to show how the assembly of multiple different parts can carry various penalties and add cost through assembly time. The goal is to reduce these penalties and time to reduce cost and to make the product more effective and to make the process more efficient. Tables 20 through 23 show the assembly order and penalties of each sub-assembly.

5.1.1 Rail

As mentioned before, the rails of Design 1 are constructed mostly of angle iron and square tube steel. The rail sub-assemblies of Design 1also include two small sub-assemblies as parts to fully construct the rail sub-assembly. These two small sub-assemblies are frames made of angle iron. In this study the focus is on how these angle iron and square tube steel parts are assembled together to create a rail. Therefore, any fastening method is examined in this analysis and different forms of fastening carry different penalties with them. In addition, how the part and fastener are retrieved, handled, and inserted carries different penalties. Table 20 shows the analysis of how all the parts in one rail are assembled. It also shows how all the parts to assemble the angle iron frame, which is a part in the rail assembly, are assembled. The DFA table in Table 20 shows the number of parts in the assembly, the theoretical number of parts, the assembly index, the time to assemble each part, and the total assembly time. The table helps a designer to evaluate the product using DFA guidelines.

Table 20. DFA Table for Design 1 Rail Sub-Assembly (frame assembly included)

Part	Retrieve			Handle			Insert						# Parts	Assembly Index	Part Required	Time to Assemble part	Total Time
							AL = alignment difficult NTD = not top down HIP = hold in place			OB = obstructed RES = resistance							
1 Rail Frame DFA	Small <12mm (+1) <2mm (+2)	Tangled (+2)	Flexible (+2)	No end symm (+2)	No insert symm (+2) (+1) if clear	Heavy or tools needed (+2)	AL (+2)	OB (+2)	NTD (+2)	RES (+2)	HIP (+2)	FASTEN Twist (+1) Screw (+3)					
Angle Iron Frame																	
Base Angle Iron											2		1	2	1		
Vertical Support Angle Iron (welded)						2					2		4	16	0	30	120
Top Angle Iron Rail							2				2		1	4	0	3	3
Weld Top Angle Iron to Supports						2		2						16	///	30	120
Axle Plates (welded)						2	2		2				3	18	1	53	159
SUM of Penalties						6	4	2	2		6						
												Total	9	56	2		402
										Total for Two Frames			18	112	4		804
Rail Assembly																	
Angle Iron Frame				2		2					2		1	6	1	3	3
6" Square Tube Steel							2				2		12	48	0	3	36
Angle Iron Frame				2		2	2				2		1	8	0	3	3
Bolts(attach tube steel to frame)				2			2						6	24	0	5	30
Nuts(attach tubesteel to frame)	1					2	2		2			1	6	48	0	12	72
Perforated Metal Guide Rail									2				8	16	8	3	24
Bolts(attach guide rail to frame)				2					2				16	64	0	5	80
Nuts(attach guide rail to frame)	1					2	2		2			1	16	128	0	12	192
Shaft						2	2						2	8	1	17	34
Collar						2			2			3	2	14	2	19	38
Timing Belt Pulley						2							2	4	2	10	20
Collar						2						3	2	10	2	19	38
SUM of Penalties	2			8		16	12		10		6	8					
												Total	74	378	16		570
Goal: minimize assembly index and parts count								Part required if:		relative motion different material (dis)assembly impossible without			Parts reduction:		58		

As can be seen in Table 20 for one angle iron frame, the assembly index is 56, the total number of parts is 9 and the estimated total time for assembly is 402 seconds or 0.112 hours. The goal is to minimize the assembly index and parts count to decrease the difficulty and assembly time. After performing a parts analysis, the theoretical number of parts for this single frame is 2.

From Table 20 for one rail assembly, the total number of parts is 74, the assembly index is 378, and the estimated assembly time is 570 seconds or 0.16 hours. Using equation (1) from Chapter 2, the improvement potential for one Design 1 rail is 78.4%. The design of the rails in Design 1 is considered poor and is in desperate need of redesign because the improvement potential is greater than 60% [12]. The design efficiency, which is based on the time of assembly, can also be calculated using equation (3) from Chapter 2. The design efficiency for the rails is 8.42%. A cost estimation for the assembly of the rail can also be calculated, using equation (15), to help illustrate how the assembly can affect the total cost of a product.

$$C_a = C_o t_{ma} \tag{15}$$

where C_a is the cost of assembly, C_o is the cost rate, and t_{ma} is the estimated total assembly time for the product. For this study the cost rate for assembly will be the hourly minimum wage for Nebraska. The hourly minimum wage for Nebraska is $9.00 per hour [27]. Using equation (15), the cost of assembly for one Design 1 rail is $1.44. The cost for assembling the angle iron frames should also be included in the total cost of the rail assembly. Using equation (15), the estimated cost to assemble the two angle iron frames, which are included in one rail assembly, is $2.01. Therefore, the estimated total cost to assemble one rail assembly is $3.45. The estimated total cost to assemble two rails is $6.90.

Since the foot orientation rail was included in the DFM analysis of the rail sub-assembly it will also be included in the DFA analysis. The foot orientation rail is a separate assembled part but is considered as part of the entire rail sub-assembly. The assembly index is 436, the total number of parts is 72, and the estimated total time for assembly is 540 seconds or 0.15 hours. This can be seen in Table 21. After performing a parts analysis, the theoretical number of parts for a single foot orientation rail is 7. Using equation (1), the improvement potential for one foot orientation rail is 90.3%. Similar to the rail, the design of the foot orientation rails is considered poor and is in desperate need of redesign because the improvement potential is greater than 60% [12]. Using equation (3), the design efficiency for the foot orientation rails is 3.89%. Using equation (15) to calculate a cost estimation for assembly, with a cost rate of $9.00 per hour, the estimated cost of assembly for one foot orientation rail is $1.35.

There is one rail and one foot orientation rail per sub-assembly. So the estimated cost to assemble one rail sub-assembly is $4.80. The total estimated cost for assembling two rail sub-assemblies is $9.60.

Table 21. DFA Table for Design 1 Foot Orientation Rail Assembly

Part	Retrieve			Handle			Insert						# Parts	Assembly Index	Part Required	Time to Assemble Part	Total Time
							AL = alignment difficult			OB = obstructed							
							NTD = not top down			RES = resistance							
							HIP = hold in place										
	Small	Tangled	Flexible	No end symm	No insert symm	Heavy or tools needed	AL	OB	NTD	RES	HIP	FASTEN					
	<12mm (+1)				(+2)							Twist (+1)					
	<2mm (+2)	(+2)	(+2)	(+2)	(+1) if clear	(+2)	(+2)	(+2)	(+2)	(+2)	(+2)	Screw (+3)					
Square Tube Steel											2		2	4	1		
Bolt (to connect tube steel)				2			2						2	8	0	5	10
Nut	1					2	2		2			1	2	16	0	12	24
Bent Iron					2				2		2		1	6	0	3	3
Bolt				2			2		2				2	12	0	5	10
Nut	1					2	2		2			1	2	16	0	12	24
Wheel					2				2		2		2	12	2	3	6
Bolt				2			2						8	32	0	5	40
Nut	1					2	2		2			1	8	64	0	12	96
Wooden Block									2		2		1	4	0	3	3
Cam Follower					2						2		1	4	1	3	3
Bolt				2			2		2				4	24	0	5	20
Nut	1					2	2		2			1	4	32	0	12	48
Wooden Block											2		1	2	0	3	3
Cam Follower					2						2		1	4	1	3	3
Bolt				2			2		2				4	24	0	5	20
Nut	1					2	2		2			1	4	32	0	12	48
Bent Iron					2						2		1	4	0	3	3
Bolt				2			2		2				2	12	0	5	10
Nut	1					2	2		2			1	2	16	0	12	24
Wheel					2				2		2		2	12	2	3	6
Bolt				2			2						8	32	0	5	40
Nut	1					2	2		2			1	8	64	0	12	96
SUM of Penalties	7			14	12	14	28		30		18	7					
												Total	72	436	7		540
Goal: minimize assembly index and parts count								Part required if:		relative motion			Parts reduction:		65		
										different material							
										(dis)assembly impossible without							

5.1.2 Foot Pedal

Similar to the rails of the first design, the foot pedal sub-assembly is constructed of mostly square tube steel. Other parts that are used to construct one foot pedal are two carriage plates, six wheels, and one caster. However, for this DFA study only four wheels will be assembled to the foot pedal. The other two wheels are assembled after the foot pedal is assembled to the rail of the machine. The parts are assembled using bolts and nuts. Table 22 is a DFA table analysis of the assembly of one foot pedal and can be seen below. From this table, the total number of parts is 28, the assembly index is 132, and the estimated total assembly time is 223 seconds or 0.062 hours. After performing a parts analysis, the theoretical number of parts for a foot pedal is 13. Using equation (1), the improvement potential for a foot pedal is 53.6%. The foot pedal design is considered fair because the improvement potential is between 40-60% [12]. Using equation (3), the design efficiency of the foot pedal is 17.5%. Using equation (15) with a cost rate of $9.00, the estimated time to assemble one foot pedal sub-assembly is $0.56. The estimated total cost of assembly for two foot pedal sub-assemblies is $1.12.

5.1.3 Rocker

The rocker sub-assemblies are constructed of angle iron and square tube steel. The angle iron and square tube steel parts are assembled using bolts and nuts. Table 23 is a DFA table of one rocker sub-assembly. Table 23 shows the total number of parts in a rocker sub-assembly is 14, the assembly index is 78 and the estimated total assembly time is 83 seconds or 0.023 hours. After a parts analysis of the sub-assembly, the theoretical number of parts was found to be 1. Using equation (1), the improvement potential for a rocker sub-assembly is 92.9%. The design of the rocker is considered poor and is in desperate need of a redesign because the improvement potential is greater than 60% [12]. Using equation (3), the design efficiency of a rocker is 3.6%. Using equation (15) with a cost rate of $9.00 per hour, the estimated time to assemble one rocker sub-assembly is $0.21. The estimated cost to assemble two rocker sub-assemblies is $0.42.

Table 22. DFA Table for Design 1 Foot Pedal Sub-Assembly

Part	Retrieve			Handle			Insert						# Parts	Assembly Index	Part Required	Time to Assemble Part	Total Time
							AL = alignment difficult			OB = obstructed							
							NTD = not top down			RES = resistance							
							HIP = hold in place										
	Small <12mm (+1) <2mm (+2)	Tangled (+2)	Flexible (+2)	No end symm (+2)	No insert symm (+2) (+1) if clear	Heavy or tools needed (+2)	AL (+2)	OB (+2)	NTD (+2)	RES (+2)	HIP (+2)	FASTEN Twist (+1) Screw (+3)					
Steel Square Tube							2				2		5	20	1		
Shaft							2						1	2	1	17	17
Bolt				2			2						1	4	0	5	5
Nut	1					2	2		2			1	1	8	0	12	12
First Carriage Plate (outside)					2								1	2	1	3	3
Attachment Bar (weld)						2	2				2		1	6	0	45	45
Collar						2						3	1	5	0	19	19
Wheels									2		2		2	8	2	3	6
Bolt				2			2						2	8	2	5	10
Nut	1					2	2		2			1	2	16	0	12	24
Second Carriage Plate (inside)					2				2				1	4	1	3	3
Collar						2						3	1	5	0	19	19
Wheels									2		2		2	8	2	3	6
Bolt				2			2						2	8	2	5	10
Nut	1					2	2		2			1	2	8	0	12	24
Caster					2				2				1	4	1	3	3
Bolt				2			2		2				1	6	0	5	5
Nut	1					2	2	2	2			1	1	10	0	12	12
SUM of Penalties	4			8	6	14	22	2	18		8	10					
												Total	28	132	13		223
Goal: minimize assembly index and parts count								Part required if:		relative motion			Parts reduction:		15		
										different material							
										(dis)assembly impossible without							

Table 23. DFA Table for the Rocker Sub-Assembly

Part	Retrieve			Handle			Insert						# Parts	Assembly Index	Part Required	Time to Assemble Part	Total Time
							AL = alignment difficult			OB = obstructed							
							NTD = not top down			RES = resistance							
							HIP = hold in place										
	Small <12mm (+1) <2mm (+2)	Tangled (+2)	Flexible (+2)	No end symm (+2)	No insert symm (+2) (+1) if clear	Heavy or tools needed (+2)	AL (+2)	OB (+2)	NTD (+2)	RES (+2)	HIP (+2)	FASTEN Twist (+1) Screw (+3)					
3 ft Angle Iron											2		1	2	1		
Top Square Tube Steel							2				2		2	8	0	3	6
Bolts				2			2		2				2	12	0	5	10
3 ft Angle Iron					2				2				1	4	0	3	3
Nuts	1					2	2					1	2	12	0	12	24
Bottom Square Tube Steel							2	2			2		2	12	0	3	6
Bolts				2			2		2				2	12	0	5	10
Nuts	1					2	2		2			1	2	16	0	12	24
SUM of Penalties	2			4	2	4	12	2	8		6	2					
												Total	14	78	1		83
Goal: minimize assembly index and parts count								Part required if:		relative motion			Parts reduction:		13		
										different material							
										(dis)assembly impossible without							

5.2 Design 2

The second design of the rehabilitative gait machine was redesigned to create a better and more effective machine. Even though it was redesigned, different parts and sub-assemblies still had to be assembled to create the final product. Through the use of DFA concepts the rail, foot pedal, and rocker sub-assemblies were redesigned. These redesigns are then evaluated using DFA concepts to compare the improvements with the first design.

5.2.1 Rail

After evaluating the rail design from Design 1, the rail was redesigned to be only one part. The rail is manufactured from anodized aluminum and is 74 mm wide and 1500 mm long [19]. The largest factor in being able to have a rail as one part is by performing a parts analysis on the first rail. As explained in Chapter 4, there is no need for the rail to be constructed of multiple pieces of angle iron and square tube steel. All the angle iron parts can be combined and all the square tube parts can be combined. In addition, the material can be all of one type. There was no DFA table made for the rail of Design 2 because the rail is one single part. However, the improvement between the two designs can be calculated. Using equation (2) from Chapter 2, the actual improvement from Design 1 to Design 2 is 98.9%.

5.2.2 Foot Pedal

As previously mentioned, the foot pedals had to be redesigned because of the rail redesign. In addition, from the analysis made of Design 1, it was concluded that there is 53.6% improvement potential for redesign. However, the foot pedal for Design 2 was not a direct redesign of the foot pedal from Design 1 because the foot pedals had to be redesigned with specific parts because of the new rails. The new rails can only be used with matching carriages. Each foot pedal used two of these carriages and other parts to build the foot pedal. An analysis of the foot pedal design for Design 2 can be seen in the DFA table in Table 24. From Table 24, the number of parts in the foot pedal sub-assembly is 21, the assembly index is 151, and the estimated time to assemble the sub-assembly is 147 seconds or 0.041 hours. The theoretical number of parts was found after performing a parts analysis to be 8. Using equation (1) from Chapter 2, the improvement potential for the Design 2 foot pedal sub-assembly is 61.9%. The design of the foot pedals from Design 2 are considered poor and are in desperate need of redesign [12]. Using equation (3) from Chapter 2, the design efficiency of the design is 16.3%. Using equation (15) with a cost rate of $9.00, the estimated cost to assemble one foot pedal sub-assembly is $0.37. The estimated total cost to assemble the foot pedal sub-assemblies is $0.74. Now that a DFA analysis has been made for each foot pedal design, the two designs can be compared. Using equation (2), the actual improvement from Design 1 to Design 2 is 25%.

5.2.3 Rocker

The same rocker sub-assembly from Design 1 was used in the production of the Design 2 rehabilitative gait machine. The rocker for Design 2 was slightly redesigned because it had to have some additional machining done so that the machine could be adjustable. This was addressed in Chapter 4. There are no assembly differences between the two rocker sub-assembly designs. Therefore, there was 0% actual improvement made to the rocker sub-assembly.

Table 24. DFA Table of Design 2 Foot Pedal Sub-Assembly

Part	Retrieve			Handle			Insert						# Parts	Assembly Index	Part Required	Time to Assemble Fixtures	Total Time per Fixture
							AL = alignment difficult NTD = not top down HIP = hold in place			OB = obstructed RES = resistance							
	Small <12mm (+1) <2mm (+2)	Tangled (+2)	Flexible (+2)	No end symm (+2)	No insert symm (+2) (+1) if clear	Heavy or tools needed (+2)	AL (+2)	OB (+2)	NTD (+2)	RES (+2)	HIP (+2)	FASTEN Twist (+1) Screw (+3)					
Foot Carriage													1		1		
1 in Thick Aluminum Block											2		1	2	1	3	3
Bolt				2		2	2					3	2	18	0	10	20
2 in Thick Aluminum Block											2		1	2	1	3	3
Bolt				2		2	2					3	2	18	0	10	20
Hinge			2								2		1	4	1	3	3
Bolt/Screw				2		2	2					3	2	18	0	3	6
Foot Carriage									2				1	2	1	3	3
1 in Thick Aluminum Block									2		2		1	4	1	3	3
Bolt				2		2	2					3	2	18	0	10	20
Threaded Rod (welded nut)				2		2			2			3	1	18	1	10	10
Collar						2						3	1	5	0	19	19
Foot Pedal Plate				2	2				2		2		1	8	1	3	3
Bolt				2		2	2					3	2	18	0	5	10
Nut	1					2	2		2			1	2	16	0	12	24
SUM of Penalties	1		2	14	2	16	12		10		10	22					
												Total	21	151	8		147
Goal: minimize assembly index and parts count								Part required if:		relative motion different material (dis)assembly impossible without			Parts reduction:		13		

5.3 Discussion

The data presented in this chapter helps to show how using DFA techniques or guidelines early in the design process can help reduce cost and eliminate the need for redesign. This was done by analyzing DFA tables of the rail, foot pedal, and rocker sub-assemblies for both designs. The DFA tables present information about how a part was retrieved, handled, and inserted into an assembly. The DFA tables show the total number of parts, the assembly index, the theoretical number of parts, and the estimated assembly time of each assembly. Tables 25 and 26 show a summary of the data from the DFA tables.

Table 25. Design 1 DFA Table Data

	Number of parts	Assembly Index	Theoretical Number of Parts	Improvement Potential	Assembly Time	Total Cost
Rail:	74	378	16	78.40%	570	$2.88
-Frame	9	56	2		804	$4.02
-Orientation Rail	72	436	7		540	$2.70
Foot Pedal	28	132	13	53.60%	223	$1.12
Rocker	14	78	1	92.90%	83	$0.42
Total		1080				**$11.14**

Table 26. Design 2 DFA Table Data

	Number of parts	Assembly Index	Theoretical Number of Parts	Actual Improvement	Assembly Time	Total Cost
Rail	1	0		98.90%	0	$0
Foot Pedal	21	151	8	25%	147	$0.74
Rocker	14	78	1	0%	83	$0.42
Total		229				**$1.16**

The total cost in the right hand column of Tables 25 and 26 is the cost to assemble all the specific sub-assemblies. For example, for one Design 1 machine there are two rail sub-assemblies which includes four frames and two orientation rails. The cost in Table 25 shows the cost to assemble the two rail sub-assemblies, the four frames and the two orientation rails. The assembly time is given in seconds. The other data in Tables 25 and 26 is just for one sub-assembly. Therefore, the total assembly index for all the sub-assemblies in Design 1 is 2160 and the total assembly index for all the sub-assemblies in Design 2 is 458.

Comparing Tables 25 and 26, one can see that there is a significant improvement in the rail design. Since the rail is only one part it doesn't take any time to assemble it and therefore there is no cost due to assembly incurred. There is also no assembly index because the rail did not have to assembled, therefore no difficulty in assembling. There was also good improvement seen in the foot pedal design. There was a 7-part decrease in the amount of parts which resulted in an improvement of 25%. There was also a 14.4% increase in the assembly index but a 34.1% decrease in the assembly time. This means that the foot pedal sub-assembly for Design 2 was harder to assemble but the operations were quicker. The reason why the first design is easier to assemble but has a larger assembly time probably corresponds to the welding that was done for the attachment bar on the carriage plate. Welding takes longer than a usual nut and bolt assembly but the nut and bolt assembly requires holes to be drilled into the parts so that they may be joined. There are no improvements for the rocker sub-assembly because the same rocker assembly was used in both designs.

As can be seen, there is an 89.6% cost reduction for the assembly of these three main sub-assemblies. This helps to prove that if DFA guidelines were used during the design stage of the product, a reduction in cost can be made. The assembly process can also be improved and be easier and more efficient.

An important fact to note is that the times given for assembly are more of an average overall of the assembly operation, which includes retrieving, handling, and inserting. However, time is primarily based on the insertion method. The times for assembling a part or fastener do not take into account the specifics of the assembly. It should also be noted that there was not a time for assembly for all operations included in the assembly of these sub-assemblies. Therefore, for unknown assembly operation times, a time of 3 seconds was considered appropriate. As stated in Chapter 2, 3 seconds is the average time for a basic assembly (handling and insertion) for a part. For these reasons these assembly times are only estimates and cannot be used as an exact time. For future research it could be advantageous to quantify the assembly times into specific retrieving, handling, and inserting operations for more exact time estimations.

In addition to looking at the design from an assembly time stand point, the assembly index can also provide interesting insights. The assembly index does take into account the specifics of the retrieving, handling, and insertion. The DFA tables in Tables 20-24 also show a sum of specific penalties associated with assembling a part. As can be seen in Table 20, the highest reoccurring penalty in the rail assembly of Design 1 is a handling penalty of a part being heavy or needing tools to install. The sum of penalties for the penalty of heavy or tools needed is 16. This fact of having to lift heavy parts or using tools to assemble attributes to the difficulty of assembly. However, the highest amount of penalties came from the insertion of the parts. Insertion had a total sum of penalties of 36. This means that most of the time and difficulty can be attributed to insertion.

As can be seen in Table 22, the most reoccurring penalty in the foot pedal assembly of Design 1 is the alignment for insertion. Insertion of all the parts also had the highest sum of penalties of 60. This means that most of the time and difficulty can be attributed to insertion. As can be seen in Table 23, the rockers' most reoccurring individual penalty was also alignment for insertion. Insertion of all the parts also had the highest sum of penalties of 30. This means that most of the time and difficulty can be attributed to insertion as well.

The rail assembly for Design 2 has no penalties from assembly because it was not assembled. As can be seen in Table 24, the most reoccurring penalty in the foot pedal assembly of Design 2 is fastening for insertion. This means that the use of fasteners attributed the most difficulty and time in assembling the foot pedal. Insertion of all the parts also has the highest sum of penalties of 54. This also means that most of the time and difficulty can be attributed to insertion. The rocker in Design 2 is the same as Design 1 and therefore has the same penalty distribution.

The fact that insertion played the largest role in the assembly index for the assembly of the sub-assemblies presented helps defend the time estimate. The time for assembly given in the tables is mostly dependent on insertion. This is sufficient for this estimate because the insertion of parts in the sub-assemblies had the largest sum of penalties which means insertion can be attributed for affecting the assembly time the most. Therefore, if the designer can make the insertion of parts easier for assembly he can decrease the difficulty and assembly time, which will help lower cost. This is especially true for fasteners, because they carry an extra insertion penalty with them. It can also be noticed in Table 20-24 that the fasteners (nut and bolt) have the largest assembly time associated with them. The designer can make the insertion of parts or fasteners easier for assembly to decrease difficulty and assembly time by incorporating DFA techniques in the design process.

CHAPTER 6 – CONCLUSION

A pediatric rehabilitative gait machine that can be adjustable was designed and built by Stolle [3]. The machine was built with the goal of creating a cost effective rehabilitation machine that could be affordable for use by hospitals, small clinics and in-home patient use. Two design iterations of the rehabilitation machine were built. The first design or Design 1 was initially designed and built, but after it was determined that the machine was not functional and needed improvements, a second design or Design 2 was made. In this study a DFM/DFA analysis was made of both design iterations. The goal was to show the potential advantages of using DFM/DFA during the design process of a product's life cycle. This was shown through the comparison of the DFM/DFA analysis of Design 1 and Design 2. Tables 27 and 28 show the manufacturing and assembly data for all the main sub-assemblies in the machine and the data for the whole machine itself.

Table 27. Design 1 Data Summary

	Machining Cost	Material Cost	Manufacturing Cost	Assembly Cost	Assembly Index
Rail	$525.05	$427.89	$952.94	$9.60	1740
Foot Pedal	$194.68	$164.85	$359.53	$1.12	264
Rocker	$138.28	$45.54	$183.82	$0.42	156
Cams	$1,392.00	$805.64	$2,197.64	$0.00	0
Sub-Assembly Total	$2,250.01	$1,443.92	$3,693.93	$11.14	2160
Machine	$2,250.01	$4,606.03	$6,856.04	$19.35	2360

Table 28. Design 2 Data Summary

	Machining Cost	Material Cost	Manufacturing Cost	Assembly Cost	Assembly Index
Rail	$0.00	$660.00	$660.00	$0.00	0
Foot Pedal	$98.91	$566.44	$665.35	$0.74	302
Rocker	$153.98	$45.54	$199.52	$0.42	156
Cams	$348.00	$85.46	$433.46	$0.00	0
Sub-Assembly Total	$600.89	$1,357.44	$1,958.33	$1.16	458
Machine	$600.89	$3,515.90	$4,116.79	$5.76	1282

6.1 Design 1

In Chapters 4 and 5 a DFM and DFA analysis was made on the main sub-assemblies of Design 1. These sub-assemblies include the rails, foot pedals, and rockers of the machine. The cams were also analyzed using DFM. A cost estimation was made for both manufacturing and assembly to illustrate the advantages of incorporating DFM/DFA into a design process. This shows how DFM/DFA can make the design more cost effective. It was determined that the total cost estimate to machine these sub-assemblies and cams is $2,250.01 and this can be seen in Table 27. It was also determined that the estimated total manufacturing cost, which for this study is the machining and material cost, for these sub-assemblies and cams is $3,693.93 and can be seen in Table 27.

After a DFA analysis was performed on Design 1 it was determined that the estimated total assembly cost for these sub-assemblies is $11.14 and this can be seen in Table 27. The assembly cost estimations were primarily based on the time for insertion. The total assembly index, which is a measurement of the difficulty to assemble, for these sub-assemblies is 2160.

6.1.1 DFM/DFA Analysis of the Entire Machine

Performing the same DFM/DFA analysis used in Chapters 4 and 5, an analysis is made on the whole Design 1 gait rehabilitation machine. The machining cost estimate for this analysis is going to be the total machining cost estimate made for the sub-assemblies and cams. There was additional minimal machining done for the machine other than the sub-assemblies and cams. Therefore, the machining cost estimate for the sub-assemblies and cams is a sufficient estimate for the machine as a whole. The material cost for the

Design 1 gait rehabilitative machine can be found in the BOM of Design 1 in Appendix A. The total material cost, which includes the raw material and ordered parts (excluding fasteners), is $4,606.03. Therefore the estimated total manufacturing cost is $6,856.04.

After performing a DFA analysis, through the use of a DFA table, it was found that the estimated time to assemble the whole machine is 4,445 seconds or 1.23 hours and this can be seen in the DFA table in Appendix C. Adding the time to assemble the sub-assemblies (except for the rail because it is included in the DFA table) the estimated total assembly time is 7,745 seconds or 2.15 hours. The estimated total cost of assembly, using the Nebraska minimum wage as a cost rate of $9.00 [27], can be calculated using equation (15). The estimated total cost of assembly is $19.35 and can be seen in Table 27. The assembly index is 2,360 and can be seen in the DFA table for Design 1 in Appendix C and Table 27. This is the assembly index to assemble all parts and sub-assemblies together to create the final product.

The total number of parts, given in the DFA table, for Design 1 is 427. After performing a parts analysis, the theoretical number of parts is 185 parts. Using equation (1) from Chapter 2, the improvement potential for Design 1 is 56.7%. Design 1 is considered fair because the improvement potential is between 40-60% [12]. The Design 1 gait rehabilitation machine can be seen in Figure 12.

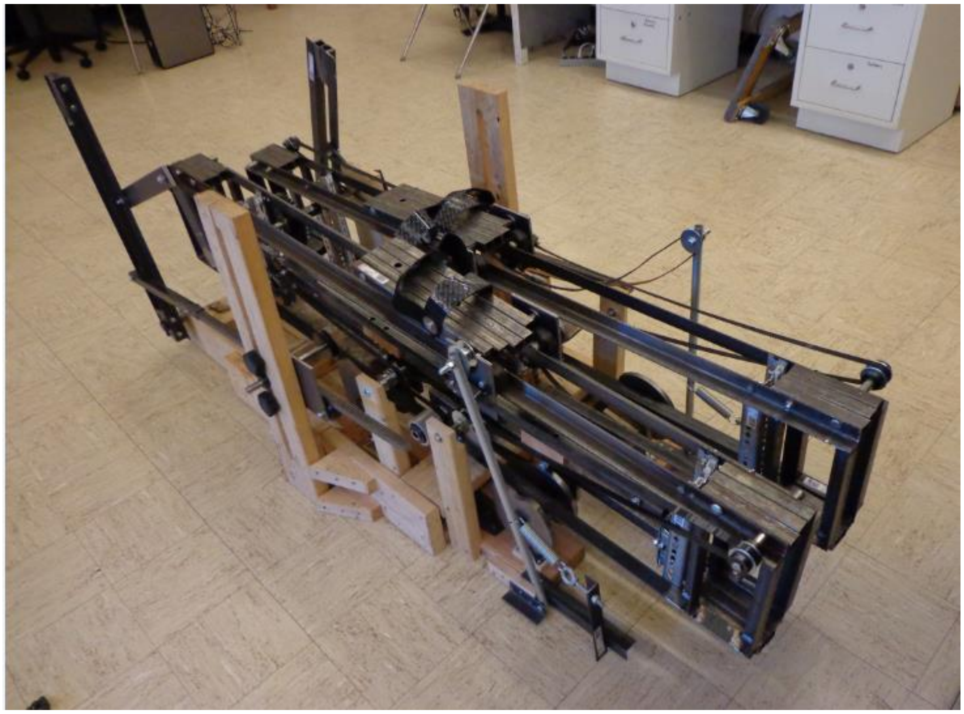

Figure 12. Design 1 Gait Rehabilitation Machine

6.2 Design 2

In Chapters 4 and 5 a DFM/DFA analysis was made of the main sub-assemblies of Design 2. The sub-assemblies included the rails, foot pedals, and rockers of the machine. The cams were also analyzed through DFM. Cost estimations were made to illustrate the advantages of using DFM/DFA. It was determined that the estimated total cost to machine these sub-assemblies for Design 2 is $600.89 and this can be seen in Table 28. This shows that the redesign of these sub-assemblies resulted in a 73.3% decrease in machining cost. This is primarily influenced by the redesign of the rail sub-assembly and the cams. Redesigning the machine from Design 1 resulted in a reduction of cams which reduced the manufacturing cost of cams by 80.3% and this can be seen in Table 28. The rails of Design 2 are purchased pre-manufactured anodized aluminum rails. They required no additional machining. These rails required special carriages to be used with them. Because of this the machining cost of the foot pedals decreased by 49.2% but the material cost of the foot pedals increased by 243.6%. However, because the machining cost was so high for Design 1, there was still a 47% decrease in the estimated total manufacturing cost for these sub-assemblies, which was $1,958.33 for Design 2 and this can be seen in Table 28.

After a DFA analysis was performed on Design 2 it was determined that the estimated total assembly cost of these sub-assemblies is $1.16 and this can be seen in Table 28. The redesign of these sub-assemblies resulted in an 89.6% cost reduction for assembly. This cost reduction can be attributed to the 98.9% design improvement to the rail sub-assemblies and a 25% design improvement of the foot-pedal sub-assemblies. The total assembly index for assembling these sub-assemblies is 458. This results in a 78.8% reduction in assembly index or difficulty to assemble. These improvements in assembly can also be attributed to the redesign of the rails because the rails for Design 2 did not need to be assembled.

6.2.1 DFM/DFA Analysis of the Entire Machine

Performing the same DFM/DFA analysis from Chapters 4 and 5, an analysis was made for the whole Design 2 gait rehabilitation machine. The machining cost estimate for this analysis is going to be the total machining cost estimate made for the sub-assemblies and cams. There was additional minimal machining done for the machine other than the sub-assemblies and cams. Therefore, the machining cost estimate for the sub-assemblies and cams is a sufficient estimate for the machine as a whole. The material cost for the rehabilitative machine can be seen in the BOM for Design 2 in Appendix B. The total material cost, which is the raw material and ordered parts (excluding fasteners), is $3,515.90. This corresponds to an overall 23.7% reduction in material cost. The manufacturing cost for the Design 2 machine is $4,116.79. This corresponds to an overall 40% reduction in manufacturing cost from the first design.

After performing a DFA analysis of Design 2, using a DFA table, the estimated assembly time to assemble the whole machine is 1,831 seconds or 0.51 hours. This can be seen in the Design 2 DFA table in Appendix D. To obtain the total assembly time for the machine, the foot pedal and rocker sub-assemblies' assembly times need to be added. The estimated total assembly time for the Design 2 gait rehabilitation machine is 2,291 seconds or 0.64 hours. The estimated total cost of assembly can be calculated using equation (15) with a cost rate of $9.00. Therefore, the estimated total cost of assembly for Design 2 is $5.76. This corresponds to a 70.2% reduction in assembly cost. The assembly index for Design 2 is 1,282. This corresponds to a 45.7% decrease in difficulty of assembly.

The total number of parts, from the Design 2 DFA table, of Design 2 is 218. Knowing the number of parts from Design 1 and using equation (2) from Chapter 2, the actual improvement can be found to be 48.9%. The Design 2 gait rehabilitation machine can be seen in Figure 13.

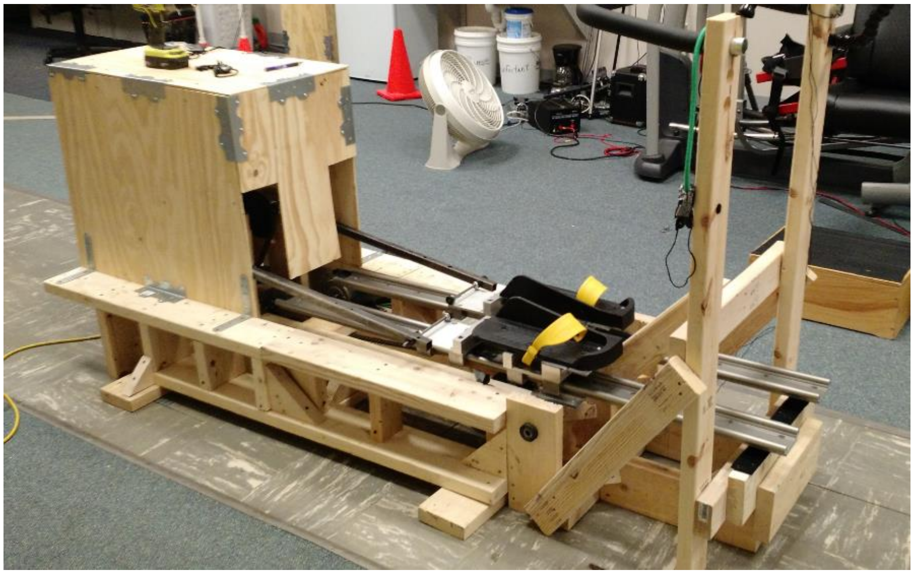

Figure 13. Design 2 Gait Rehabilitation Machine

6.3 Conclusion

Throughout this study two iterations of a gait rehabilitation machine were compared using DFM and DFA principles. The data presented throughout this study show that using DFM and DFA during the design process can help a designer to analyze their design and make their product more cost efficient and effective. Even though the DFM and DFA techniques were applied to the designs after the two machines were built, these techniques show cost estimations for manufacturing and assembly and show where improvements can be made. If the original designer would have incorporated DFM and DFA into the design of the machine initially, he could have noticed where improvements needed to be made in the design before the machine was built. If DFM and DFA would have been incorporated into Design 1, then the redesign or Design 2 may not have been necessary. If only Design 2 were manufactured and assembled the designer would have saved a total of $6,875.39 for manufacturing and assembling Design 1. This total savings is based on a machining cost rate of $58 per hour and an assembly cost rate of $9 per hour. The machining cost rate is an established rate by a professional machine shop and includes employees' salaries and benefits, tooling cost, and overhead cost. Therefore, the machining cost presented in this study represents a realistic cost. The assembly cost rate is simply just an employees' hourly minimum wage. It does not include any benefits, or overhead cost. Therefore, the assembly cost presented in this study represents the lower bounds of what the cost of assembly could be.

If overhead, benefits, etc. were included in the cost rate for assembly, the cost rate would be higher and therefore the cost for assembly would change significantly. If it is assumed that the assembly cost rate for a product assembly factory is similar to the established machining cost rate of $58/hour for the UNL machine shop then the assembly cost for this study would be 6 times as much. This would greatly increase the assembly cost and total cost to create the two gait rehabilitation machine iterations and could provide a more realistic cost estimation.

When DFM disagrees with DFA or vice versa in the design of a part or product, it is up to the designer which problem outweighs the other. The easiest way is to look at the cost to assemble and the cost to manufacture the part, compare them, and then choose the cheapest option. However, in addition to the cost, the designer needs to look at how these decisions affect the parts around it and whether or not it makes the neighboring parts more expensive to manufacture or assemble. The designer has to choose the best option for the design of the product as a whole.

The goal of this project was to show how applying DFM and DFA into the design process of a product can make the process more efficient and reduce the overall cost of the product. In addition, the project also aims to provide data that can be used to design a third iteration gait rehabilitation machine. This was done through the comparison of DFM/DFA analysis of the gait rehabilitative device iterations.

There is a fair amount of uncertainty in comparing DFM and DFA analysis and cost estimations of the two design iterations. Elements of uncertainty (limitations of this study) include:

- The theoretical machining times don't take into account the material strength of the machine itself, the vibration of the machine, tolerances, and the damages from heat produced by the interaction of the cutter with the material.
- The machining cost estimates for the two gait rehabilitation machines only takes into account the machining cost to produce the rail, foot pedal, rocker sub-assemblies and the cams.
- The assembly cost rate is not a fully realistic cost rate. It doesn't take into account overhead and benefits.
- The times for assembling parts into the product assembly are estimations based on a similar task. They are not the exact times for the given operation.
- For non-relatable assembly operations an assembly time of 3 seconds (an accepted average) was used.
- The cost of fasteners was not included in the material cost.

6.4 Future Work

Future work can still be done with this study. A new design of the gait rehabilitative machine can be made based on the results of the DFM and DFA analysis of Design 2. This new design can then be analyzed during the design stage, using DFM and DFA, to find the most efficient and effective design possible. A cost analysis can then be made to compare with Design 2 to illustrate the improvements that were made to the design.

After performing a DFM and DFA analysis on Design 2, it can be seen that the foot pedal and rocker sub-assemblies could use a further redesign. As can be seen in Table 26 in Chapter 5, a rocker can be redesigned to be one part and a foot pedal can be redesigned to be 8 parts. This parts reduction can result in a reduction of additional machining that needs to be done to create these sub-assemblies. In addition, a new design which doesn't use cams could greatly reduce the manufacturing cost. This is because the cams require complex machining, which can be expensive, and a large amount of material for just two parts. The improvement potential of Design 2 is 58.7% which means that the design is fair.

This study can also be used to show the impact using DFM and DFA can make in product design. Through the use of these methods a designer can discover the problem areas in the design and can exploit them and find efficient alternatives. A designer can save time and money by limiting the amount of additional machining that needs to be done and by finding the most efficient way to assemble the parts in the product.

Material accounts for most of the manufacturing cost for a product. For Design 1 it accounts for 67.2% and for Design 2 85.4%. Therefore, a designer needs to find the most efficient way to use this material. The designer should find a skilled professional machinist to machine the material if needed. An inexperienced machinist can add unwanted time and money by using incorrect feeds and speeds and other specific machining parameters. In addition, as can be seen in Chapter 5 and the DFA tables in Appendices C and D, assembly time is heavily influenced by how a part is inserted into an assembly or how two parts are joined. It is important for the designer to use these methods to find alternative ways to assemble parts which limit the difficulty of inserting. This will help save time and money and make the assembly easier. This thesis presents a designer with a method and reason for applying DFM and DFA principles. This thesis shows that if a designer knows and consciously uses these principles during the design of a product then he can obtain a cost efficient and effective product with a minor need for redesign.

CHAPTER 7 – REFERENCES

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APPENDIX A –DESIGN 1 BILL OF MATERIALS

List of Ordered Parts

Part Number:	Part Description:	Biller:	Unit Cost:	Qty:	Total Cost:
6831K14	1 1/4" O.D. , 3/8" bore track follower	McMaster	$23.17	8	$185.36
8735K11	1/8" by 1/2" by 12" long rectangular Teflon strip	McMaster	$7.29	1	$7.29
61125K69	5-lobe threaded knob	McMaster	$3.17	4	$12.68
6384K76	5/8" steel bearing	McMaster	$11.82	1	$11.82
6412K15	5/8" inner bore one-piece shaft coupler with set screws	McMaster	$12.20	2	$24.40
6384K45	3/8" steel bearing	McMaster	$10.19	2	$20.38
6435K15	5/8" bore one-piece collar	McMaster	$2.06	16	$32.96
98830A150	Oversized 3/16" by 3/16" keystock	McMaster	$0.93	4	$3.72
6436K18	1" diameter bore, 2-piece clamping	McMaster	$5.44	1	$5.44
6435K18	1" diameter bore, 1-piece clamping	McMaster	$2.74	6	$16.44
6435K15	5/8" diameter bore, 1-piece clamping	McMaster	$2.06	8	$16.48
6384K84	1" diameter bore, 2" O.D., double sealed bearing	McMaster	$18.63	2	$37.26
6384K76	5/8" diameter bore, 1 3/8" O.D., double sealed bearing	McMaster	$11.82	8	$94.56
6384K45	3/8" diameter bore, 1 1/8" outer diameter, double-sealed bearing	McMaster	$10.19	4	$40.76
5909K11	10-mm bore thrust bearing cage	McMaster	$3.70	8	$29.60
5909K71	10-mm bore thrust bearing washers	McMaster	$1.23	16	$19.68
3374K12	2 1/4" O.D., 2-piece machinable bore	McMaster	$13.89	2	$27.78
2299K35	35-tooth ANSI-40 sprocket	McMaster	$29.41	2	$58.82
6325K79	12-pitch, 1.25" pitch diameter steel plain-bore spur gear	McMaster	$27.03	1	$27.03
6384K45	3/8" steel bearing	McMaster	$10.19	6	$61.14
6384K76	5/8" steel bearing	McMaster	$11.82	1	$11.82
6384K79	3/4" shaft diameter, 1 5/8" O.D., double-sealed bearing	McMaster	$15.37	8	$122.96
6384K84	1" shaft diameter, 2" O.D., double-sealed bearing	McMaster	$18.63	4	$74.52
6384K76	0.625" diameter, 1.375" O.D. double-sealed bearing	McMaster	$11.82	4	$47.28
1497K161	0.75" diameter fully keyed shaft	McMaster	$21.20	4	$84.80
6435K16	0.75" diameter single-piece collars	McMaster	$2.43	16	$38.88

List of Ordered Parts Continued…

Part Number:	Part Description:	Biller:	Unit Cost:	Qty:	Total Cost:
6435K18	1" diameter single-piece collars	McMaster	$2.74	4	$10.96
BXL40	100 mm long, 40 -tooth XL timing belt pulley stock	Misumi	$42.23	1	$42.23
BXL30	100 mm long, 30-tooth XL timing belt pulley stock	Misumi	$41.14	1	$41.14
BXL24	100 mm long, 24 -tooth XL timing belt pulley stock	Misumi	$36.90	2	$73.80
MTPB40XL050-A-PUG	40-tooth, 5/8" bore steel XL timing belt pulley	Misumi	$25.30	2	$50.60
TBN490XL050	1/2" wide, 1244 mm lonng, single sided closed end, rubber XL timing belt	Misumi	$10.10	2	$20.20
TBN630XL050	1/2" wide, 1600.2 mm long, single sided closed end, rubber XL timing belt	Misumi	$13.30	3	$39.90
TBOG-XL050-1518	1/2" wide, 1518 tooth, 7710 mm long, single sided closed end, rubber XL timing belt	Misumi	$182.00	1	$182.00
	Shepherd 5" Gray Rigid TPR Caster	Menards	$7.99	2	$15.98
	Shepherd 2" Rigid Rubber Caster	Menards	$1.75	8	$14.00
	Each set includes 4 -54mm diameter skateboard wheels and 8 ABEC-9	Ebay	$10.99	3	$32.97
	53mm Black set of 4 skateboard wheels and 8 ABEC-7 bearings	Ebay - Downhillstor	$10.00	2	$20.00
6295K143	12-pitch, 3/4" wide, 6' long steel gear	McMaster	$74.95	1	$74.95
6325K79	12-pitch, 1.25" pitch diameter steel plain-bore spur gear	McMaster	$27.03	2	$54.06
6384K84	1" Bore, 2" O.D. double- sealed steel ball bearing	McMaster	$18.63	4	$74.52
6384K76	5/8" bore, 1 3/8" O.D. double-sealed steel ball bearing	McMaster	$11.82	4	$47.28
89955K801	1" O.D. cold-drawn steel tube, 0.25" wall thickness - 3 ft long	McMaster	$50.05	1	$50.05
1346K29	5/8" Dia Drive Shaft - 6 ft long	McMaster	$49.58	1	$49.58
6215K75	Base/Face-Mount DC Motor, 90V DC, NEMA 56C, 3/4 hp, 5/8" shaft dia	McMaster	$752.69	1	$752.69
7793K51	AC to DC Motor Speed Control, Nonreversing, Indoor Enclosure	McMaster	$287.08	1	$287.08
6261K173	Roller Chain, ANSI Number 40, 1/2" Pitch - 8 ft long	McMaster	$36.32	1	$36.32
2500T41	5/8" bore, 9-tooth hardened-tooth finished sprocket	McMaster	$14.46	1	$14.46
3018T24	Galvanized Steel Eyebolt with Nut and Shoulder, 5/16"-18 Thread Size, 3-1/4" Shank Length	McMaster	$5.31	2	$10.62
9654K326	Steel Extension Spring, 5.0" Length, .500" OD, .072" Wire - pkg of 6	McMaster	$11.30	1	$11.30
8978K17	Rigid Aluminum Tubing, 5/8" OD, .495" ID, .065" Wall Thickness - 6 ft long	McMaster	$19.94	1	$19.94
	Grip Fast 3/8" ID: 13/32" OD: 1-1/2" Zinc-Plated Fender Washers (6 Pieces)	Menards	$0.99	4	$3.96
				Total	**$3,144.45**

List of Raw Material

Machine Component:	Part Number:	Description (material):	Biller:	Cost:	Qty:	Total Cost:
1 - Frame (x2)		4 - 72" angle Iron (Top and Bottom L-track)			8	
		8 - 9 15/16 " angle Iron (For side supports of Frame)			16	
		12 - 6" Square tube Steel (End spacer/stopper of L-track - top/bottom)			24	
		2 - 60" Square tube steel (middle/inside track of frame)			4	
Foot Pedal (x2)		5 - 12" square tube steel (Bolted together to make a pedal)			10	
Rocker (x2)		2 - 3' angle Iron (To build rocker)			4	
		4 - 4" square tube steel (Top/bottom end spacer/stopper)			8	
Rack (x2)		1 - 1 1/2' square tube steel (To connect gear rack to rocker)			2	
Total Angle Iron	9017K474	1/8" by 1 1/4" by 1 1/4" - 6' long	McMaster	$15.16	13	$197.08
Total Square Tube Steel	6527K364	1" by 1" - 6 ft long	McMaster	$24.14	8	$193.12
Coupler (x2)		1 -16" long, 1/2" by 2" steel plate			2	
Crank (x2)		1 - 10" long, 1/2" by 2" steel plate			2	
Total 1/2" x 2" steel plate	8910K949	1/2" by 2" steel by 6' long	McMaster	$54.69	1	$54.69
Carriage Plates:	8910K12	1/4" by 6" by 2' long steel plate	McMaster	$47.92	1	$47.92
Center Brackets (P3)		3 1/2" by 3 1/2" by 1/2" steel plate - machined (2 per frame)			4	
Center Brackets (P4)		3 1/8" by 3 5/8" by 1/2" steel plate - machined (4 per frame)			8	
Total Steel for Brackets	8910K21	4" by 1/2" by 3' long steel plate	McMaster	$59.50	1	$59.50
	8910K21	4" by 1/2" by 1' long steel plate	McMaster	$25.65	1	$25.65
Pinion Plates		11 1/4" by 5 1/2" by 1/4" steel plate - machined (1 per gear pinion)			2	
	8910K12	6" by 1/4" - 2' long steel plate	McMaster	$47.92	1	$47.92
Cams	1388K375	18" by 18" by 1/2" thick A36 steel plate	McMaster	$201.41	4	$805.64
Wood		2" by 6" by 8" wood stud	Menards	$3.29	4	$13.16
Foot Orientation Rail Guide		Plated Slotted Steel Angle 1-1/4" x 1-1/4" x 8 ft. - 18 Gauge	Menards	$16.90	1	$16.90
		Total Material Cost:				**$1,461.58**

APPENDIX B – DESIGN 2 BILL OF MATERIALS

List of Ordered Parts

Part Number:	Part Description:	Biller:	Unit Cost ($):	Qty:	Total Cost ($):
6109K62	74mm wide guide rail for sleeve-bearing carriage - 1500mm long	McMaster-Carr	$330.00	2	$660.00
6109K61	Extra-wide sleeve-bearing carriage for 74mm wide guide rail	McMaster-Carr	$113.08	4	$452.32
89955K801	1" O.D. cold-drawn steel tube, 0.25" wall thickness - 3 ft long	McMaster-Carr	$50.05	1	$50.05
5913K64	1" bore diameter stamped-steel mounted ball bearing	McMaster-Carr	$12.69	4	$50.76
6412K16	Black Oxide Steel 0.75" Shaft Coupling	McMaster-Carr	$13.78	1	$13.78
2299K35	35-tooth ANSI-40 machinable sprocket	McMaster-Carr	$29.41	1	$29.41
7820-53R	Plastic Foot Pedal	Sears	$17.99	1	$17.99
7820-53L	Plastic Foot Pedal	Sears	$17.99	1	$17.99
93410A112	0.5" - 10 x 24" long ACME Fully Threaded Rod	McMaster-Carr	$21.83	1	$21.83
94815A107	0.5" - 10 ACME Hex Nut	McMaster-Carr	$2.60	2	$5.20
8920K26	8mm diameter steel rod - 1 ft long	McMaster-Carr	$3.06	2	$6.12
57445K24	8mm I.D. Black Oxide Steel Collar	McMaster-Carr	$4.24	6	$25.44
7208K53	0.625" diameter steel-flange mounted ball bearing	McMaster-Carr	$26.65	8	$213.20
7208K54	0.75" diameter steel-flange mounted ball bearing	McMaster-Carr	$35.52	2	$71.04
91290A460	M8 x 1.25 Metric Black Oxide Steel Socket Head Cap Screws (pack of 25)	McMaster-Carr	$8.71	1	$8.71
16175A48	6" by 5" surface mount hinge without holes	McMaster-Carr	$14.42	2	$28.84
59935K83	M8 x 1.25 Metric Ball Joint Rod End	McMaster-Carr	$6.71	4	$26.84
6436K16	3/4", 2-piece clamping collar	McMaster-Carr	$5.59	2	$11.18
2820T5	3/8" bore High-Load Dry-Running Sleeve Mounted Bearing	McMaster-Carr	$12.47	2	$24.94
2500T41	1/2" or 5/8" bore, 9-tooth hardened-tooth finished sprocket	McMaster-Carr	$14.46	1	$14.46
94563A571	3/8" hitch pin with reusable cotter pin	McMaster-Carr	$5.65	2	$11.30
6280K189	5/8" bore, 9-tooth sprocket, ANSI - 40	McMaster-Carr	$11.88	2	$23.76
6831K14	1 1/4" O.D. , 3/8" bore track follower (Cam Follower)	McMaster-Carr	$23.17	2	$46.34
5909K11	10-mm bore thrust bearing cage assembly	McMaster-Carr	$3.70	8	$29.60
5909K71	10-mm bore thrust bearing washers	McMaster-Carr	$1.23	16	$19.68
6435K18	1" diameter bore, 1-piece clamping collar	McMaster-Carr	$2.74	4	$10.96
6435K15	5/8" diameter bore, 1-piece clamping collar	McMaster-Carr	$2.06	4	$8.24
6435K16	0.75" diameter single-piece collars	McMaster-Carr	$2.43	4	$9.72
2299K35	35-tooth ANSI-40 machinable sprocket	McMaster-Carr	$29.14	1	$29.14
1497K161	0.75" diameter fully keyed shaft-12" long	McMaster-Carr	$21.20	2	$42.40
98830A150	Oversized 3/16" by 3/16" keystock	McMaster-Carr	$0.93	2	$1.86
1346K25	5/8" Dia Drive Shaft - 2ft long	McMaster-Carr	$19.26	1	$19.26
6215K75	Base/Face-Mount DC Motor, 90V DC, NEMA 56C, 3/4 hp, 5/8" shaft dia	McMaster-Carr	$752.69	1	$752.69
7793K51	AC to DC Motor Speed Control, Nonreversing, Indoor Enclosure	McMaster-Carr	$287.08	1	$287.08
6261K173	Roller Chain, ANSI Number 40, 1/2" Pitch - 8 ft long	McMaster-Carr	$36.32	1	$36.32
1497K141	5/8 diameter fully keyed shaft - 12" long	McMaster-Carr	$19.67	1	$19.67
6236K36	45-tooth ANSI-40, 5/8 dia Sprocket	McMaster-Carr	$61.58	1	$61.58
6261K173	Roller Chain, ANSI Number 40, 1/2" Pitch - 3 ft long	McMaster-Carr	$13.62	2	$27.24
				Total	**$3,186.94**

List of Raw Material

Machine Component:	Part Number:	Description (material):	Biller:	Cost:	Qty:	Total Cost:
Longitudal Power Transmission Bar		1" x 1" x 0.120" wall thickness Steel Tube - 6 ft long			2	
Rocker(x2)		2 - 3' angle Iron (To build rocker)			4	
		4 - 4" square tube steel (Top/bottom end spacer/stopper)			8	
Total Angle Iron	9017K474	1/8" by 1 1/4" by 1 1/4" - 6' long	McMaster	$15.16	2	$30.32
Total Square Tube Steel	6527K364	1" by 1" - 6 ft long	McMaster	$24.14	2	$48.28
	6527K364	1" by 1" - 3 ft long	McMaster	$14.48	1	$14.48
Coupler(x2)		1 -16" long, 1/2" by 2" steel plate			2	$2.00
Crank(x2)		1 - 10" long, 1/2" by 2" steel plate			2	$2.00
Total 1/2" x 2" steel plate	8910K949	1/2" by 2" steel - 6' long	McMaster	$54.69	1	$54.69
Metal To Build Up Foot Pedal:						
	8975K432	5" wide by 0.25" thick by 6" long Aluminum 6061 plate	McMaster	$6.11	3	$18.33
	8975K253	1.5" tall by 2" wide aluminum 6061 block- 1 ft long	McMaster	$25.25	1	$25.25
	8975K52	1" tall by 1.5" wide aluminum 6061 block - 2 ft long	McMaster	$24.05	1	$24.05
Used in connection of power transmission bar to rocker	8975K237	1" x 2" Aluminum bar - 1/2 ft long	McMaster	$10.94	1	$10.94
Cams	1388K371	8" by 12" by 1/2" thick A36 steel plate	McMaster	$85.46	1	$85.46
Wood		2" by 6" by 8" wood stud	Menards	$3.29	4	$13.16
		Total Material Cost:				**$328.96**

APPENDIX C – DFA TABLE FOR DESIGN 1

Part	Retrieve			Handle			Insert						# Parts	Assembly Index	Part Required	Time to Assemble Fixtures	Total Time per Fixture
							AL = alignment difficult NTD = not top down HIP = hold in place			OB = obstructed RES = resistance							
	Small <12mm (+1) <2mm (+2)	Tangled (+2)	Flexible (+2)	No end symm (+2)	No insert symm (+2) (+1) if clear	Heavy or tools needed (+2)	AL (+2)	OB (+2)	NTD (+2)	RES (+2)	HIP (+2)	FASTEN Twist (+1) Screw (+3)					
Wood - Frame (Base)															1		
Bottom Cam Followers				2			2				2		4	24	4	3	14
Screws				2	2	2	2					3	16	240	0	2	32
Rail Assembly																	
Angle Iron Frame				2		2	2				2		2	16	2	3	6
6" Square Tube Steel							2				2		24	96	0	3	72
Angle Iron Frame				2		2	2				2		2	16	0	3	6
Bolts (attach frame-spacer-frame)				2			2						12	48	0	5	60
Nuts (attach frame-spacer-frame)	1					2	2		2			1	12	96	0	12	144
Perforated Metal Guide Rail									2				16	32	8	3	48
Bolts(attach perforated bar to frame)				2					2				32	128	0	5	160
Nuts(attach perforated bar to frame)	1					2	2		2			1	32	256	0	12	384
Shaft						2	2						4	16	4	17	68
Collar						2			2			3	4	28	4	19	76
Timing Belt Pulley						2							4	8	4	10	40
Collar						2						3	4	20	4	19	76
Cam Assembly																	
Bearings						2	2						4	16	4	45	180
Inside Rear Cam					2				2		2		2	12	2	3	6
Board											2		2	4	0	3	6
Timing Belt Pulley Stock						2					2		2	8	0	45	90

Part	Retrieve			Handle			Insert						# Parts	Assembly Index	Part Required	Time to Assemble Fixtures	Total Time per Fixture
							AL = alignment difficult NTD = not top down HIP = hold in place			OB = obstructed RES = resistance							
	Small <12mm (+1) <2mm (+2)	Tangled (+2)	Flexible (+2)	No end symm (+2)	No insert symm (+2) (+1) if clear	Heavy or tools (+2)	AL (+2)	OB (+2)	NTD (+2)	RES (+2)	HIP (+2)	FASTEN Twist (+1) Screw (+3)					
Rear Cam Shaft							2		2				2	8	2	17	34
Key	1							2					1	3	1	10	10
Inside Rear Collar						2			2			3	2	14	0	19	38
Outside Rear Cam					2				2				2	8	2	3	6
Key	1												1	1	1	10	10
Outside Rear Collar						2						3	2	10	0	19	38
Bearings						2	2						4	16	4	45	180
Inside Front Cam					2				2		2		2	12	2	3	6
Board											2		2	4	0	3	6
Timing Belt Pulley Stock						2					2		2	8	0	45	90
Front Cam Shaft							2		2				2	8	2	17	34
Key	1							2					1	3	1	10	10
Inside Front Collar						2			2			3	2	14	0	19	38
Outside Front Cam					2				2				2	8	2	3	6
Key	1												1	1	1	10	10
Outside Front Collar						2						3	2	10	0	19	38
Rear Axle Assembly																	
Rail									2				2	4	2	3	6
Bearings						2	2		2				6	36	6	45	270
Collar						2		2			2	3	1	9	0	19	19
Timing Belt Pulley Stock						2		2			2		1	6	0	45	45
Collar						2		2			2	3	2	18	0	19	38
Timing Belt Pulley Stock						2		2			2		1	6	0	45	45

Part	Retrieve			Handle			Insert						# Parts	Assembly Index	Part Required	Time to Assemble Fixtures	Total Time per Fixture
							AL = alignment difficult NTD = not top down HIP = hold in place			OB = obstructed RES = resistance							
	Small <12mm (+1) <2mm (+2)	Tangled (+2)	Flexible (+2)	No end symm (+2)	No insert symm (+2) (+1) if clear	Heavy or tools (+2)	AL (+2)	OB (+2)	NTD (+2)	RES (+2)	HIP (+2)	FASTEN Twist (+1) Screw (+3)					
Sprocket						2		2			2	3	1	9	1	8	8
Timing Belt Pulley Stock						2		2			2		1	6	0	45	45
Collar						2		2			2	3	1	9	0	19	19
Rear Axle(steel tube)							2		2				1	4	1	17	17
Right Collar						2						3	1	5	0	19	19
Timing Belt Pulley Stock						2							1	2	0	45	45
Right End Collar						2						3	1	5	0	19	19
Left Collar						2			2			3	1	7	0	19	19
Timing Belt Pulley Stock						2							1	2	0	45	45
Left End Collar						2						3	1	5	0	19	19
Foot Orientation Rail							2		2				2	8	2	3	6
Pinion Mount																	
Steel Plate											2		2	4	2	3	6
Bearing						2	2						2	8	2	45	90
5-Lobe Threaded Knob				2	2		2		2			1	4	36	0	10	40
Shaft											2		2	4	2	17	34
Collar						2						3	2	10	0	19	38
Fender Washer									2				2	4	0	3	6
Gear						2							2	4	0	45	80
Timing Belt Pulley						2						3	2	10	2	10	20
Wheels							2				2		4	16	4	3	12
Bolt (attach wheel to plate)				2									4	8	4	5	20
Nut (attach wheel to plate)	1					2	2		2			1	4	32	0	12	48

Part	Retrieve			Handle			Insert						# Parts	Assembly Index	Part Required	Time to Assemble Fixtures	Total Time per Fixture
							AL = alignment difficult NTD = not top down HIP = hold in place			OB = obstructed RES = resistance							
	Small <12mm (+1) <2mm (+2)	Tangled (+2)	Flexible (+2)	No end symm (+2)	No insert symm (+2) (+1) if clear	Heavy or tools (+2)	AL (+2)	OB (+2)	NTD (+2)	RES (+2)	HIP (+2)	FASTEN Twist (+1) Screw (+3)					
Front Axle Assembly																	
Bearing						2	2						2	8	2	45	90
Collar						2						3	1	5	0	19	19
Crank Shaft				2	2						2		1	6	1	17	17
Collar						2			2			3	1	7	0	19	19
Shaft Coupler						2						3	1	5	1	8	8
Shaft								2					1	2	1	17	17
Collar						2						3	1	5	0	19	19
Crank Shaft				2	2						2		1	6	1	17	17
Collar						2			2			3	1	7	0	19	19
Timing Belt Pulley Stock						2							1	2	0	45	45
Sprocket						2						3	1	5	1	19	19
Shaft Coupler						2					2	3	1	7	1	8	8
Rocker Attachment																	
Bearings						2	2		2				2	12	2	45	90
Rocker Shaft													2		2	17	17
Collar						2			2			3	2	14	0	19	38
Spacer (for right rocker)									2				1	2	0	3	3
Rocker					2						2		2	8	2	3	6
Collar						2						3	2	10	0	19	38

Part	Retrieve			Handle			Insert						# Parts	Assembly Index	Part Required	Time to Assemble Fixtures	Total Time per Fixture
							AL = alignment difficult NTD = not top down HIP = hold in place			OB = obstructed RES = resistance							
	Small <12mm (+1) <2mm (+2)	Tangled (+2)	Flexible (+2)	No end symm (+2)	No insert symm (+2) (+1) if clear	Heavy or tools (+2)	AL (+2)	OB (+2)	NTD (+2)	RES (+2)	HIP (+2)	FASTEN Twist (+1) Screw (+3)					
Coupler																	
Bolt (attach crank to coupler)				2					2				2	8	2	5	10
Thrust Bearing									2				4	8	4	3	12
Thrust Bearing Washers													8		8	3	24
Coupler (rectangular bar)											2		2	4	2	3	6
Nut (attach crank to coupler)	1					2	2					1	2	6	0	12	24
Thrust Bearing							2		2		2		4	24	4	3	12
Thrust Bearing Washers							2				2		8	32	8	3	24
Bolt (attach coupler to rocker)				2			2						2	8	2	5	10
Nut (attach coupler to rocker)	1					2	2		2			1	2	16	0	12	24
Rack																	
Square Steel Tube											2		2	4	2	3	6
Wheel							2		2		2		2	12	2	3	6
Bolt (attach wheel to steel tube)				2									2	4	2	5	10
Nut (attach wheel to steel tube)	1					2	2		2			1	2	16	0	12	24
Steel Gear Rack					2		2		2		2		2	16	0	3	6
Bolt (attach gear rack to steel tube)				2			2		2				2	12	0	5	10
Nut (attach gear rack to steel tube)	1					2	2		2			1	2	16	0	12	24
Timing Pulleys Attachment																	
Bolts (attach timing pulley to frame)				2									4	8	4	5	20
Timing Pulleys									2				6	12	6	10	60
Nuts (attach timing pulley to frame)	1					2	2					1	10	60	10	12	120
Cut Pieces of Angle Iron									2		2		6	24	4	3	18
Screws (attach angle iron to wood)				2	2	2	2					3	4	44	0	3	12
Screws (attach angle iron to wood)				2	2	2	2					3	6	66	0	3	18
Bolt (connect two pieces of angle iron)				2			2		2				2	12	0	5	10
Nut (connect two pieces of angle iron)	1					2	2		2			1	2	16	0	12	24

Part	Retrieve			Handle			Insert						# Parts	Assembly Index	Part Required	Time to Assemble Fixtures	Total Time per Fixture
							AL = alignment difficult NTD = not top down HIP = hold in place			OB = obstructed RES = resistance							
	Small <12mm (+1) <2mm (+2)	Tangled (+2)	Flexible (+2)	No end symm (+2)	No insert symm (+2) (+1) if clear	Heavy or tools (+2)	AL (+2)	OB (+2)	NTD (+2)	RES (+2)	HIP (+2)	FASTEN Twist (+1) Screw (+3)					
Aluminum Tube									2		2		2	8	2	3	6
Bolt (connect tube to angle iron)				2			2		2				2	12	0	5	10
Nut (connect tube to angle iron)	1					2	2		2			1	2	16	0	12	24
Bolt (attach pulley to tube)				2			2		2				2	12	2	5	10
Pulley													2	0	2	3	6
Nut (attach pulley to tube)	1					2	2		2			1	2	16	2	12	24
Spring			2				2		2	2			2	16	2	12	24
Eye Bolt (attach spring to angle iron)				2					2				2	8	0	5	10
Nut (attach spring to angle iron)	1					2	2		2			1	2	16	0	12	24
Timing Belts			2				2		2	2			6	48	6	6	36
Foot Pedal Attachment																	
Foot Pedals				2	2				2		2		2	16	2	3	6
Wheels									2		2		4	16	4	3	12
Bolt (attach bottom wheel to pedal)				2			2						4	16	4	5	20
Nut (attach bottom wheel to pedal)	1					2	2		2			1	4	32	0	12	48
Bolt (attach timing belt to pedal)				2			2		2				4	24	0	5	20
Nut (attach timing belt to pedal)	1					2	2		2			1	4	32	0	12	48
Motor/Chain Assembly																	
Motor				2	2	2	2		2				1	10	1	3	3
Screws (attach motor to wood frame)				2	2	2	2					3	4	44	0	2	8
Chain			2				2	2	2	2			1	10	1	3	3
SUM of Penalties	18	0	6	52	30	126	102	22	110	6	68	102					
												Total	427	2360	185		4445

Goal: minimize assembly index and parts count

Part required if: relative motion
different material
(dis)assembly impossible without

Parts reduction: 209

APPENDIX D – DFA TABLE FOR DESIGN 2

Part	Retrieve			Handle			Insert						# Parts	Assembly Index	Part Required	Time to Assemble a Fixture	Total Time for Fixtures
							AL = alignment difficult NTD = not top down HIP = hold in place			OB = obstructed RES = resistance							
	Small <12mm (+1) <2mm (+2)	Tangled (+2)	Flexible (+2)	No end symm (+2)	No insert symm (+2) (+1) if clear	Heavy or tools needed (+2)	AL (+2)	OB (+2)	NTD (+2)	RES (+2)	HIP (+2)	FASTEN Twist (+1) Screw (+3)					
Wood - Frame(Base)															1		
Cam Assembly																	
Cam Flange Mounted Ball Bearings				2		2					2	3	2	18	2	8	16
Bolt (attach bearing to frame)				2			2						4	16	0	5	20
Nut (attach bearing to frame)	1					2	2		2			1	4	32	0	12	48
Cam Keyed Shafts									2				2	4	2	17	34
Sprocket (w/ collar welded to it)						2			2			3	1	7	1	19	19
Shaft Coupler						2					2	3	1	7	0	16	16
Collar						2			2			3	2	14	0	19	38
Cams					2						2		2	8	2	3	6
Keys	1						2						2	6	2	10	20
Collar						2						3	2	10	0	19	38
Rail Attachment																	
Mounted Ball Bearings				2		2					2	3	4	36	4	8	32
Collar						2					2	3	2	14	0	19	38
Rail Shaft (steel tube)									2				1	2	1	17	17
Front End Collar						2						3	1	5	0	19	19
Back End Collar						2			2			3	1	7	0	19	19
Aluminum Plate							2		2		2		2	12	0	3	6
Bolts (to attach bearing to plate)				2			2						8	32	0	5	40
Nuts (to attach bearing to plate)	1					2	2		2			1	8	64	0	12	96

Part	Retrieve			Handle			Insert						# Parts	Assembly Index	Part Required	Time to Assemble a Fixture	Total Time for Fixtures
							AL = alignment difficult NTD = not top down HIP = hold in place			OB = obstructed RES = resistance							
	Small <12mm (+1) <2mm (+2)	Tangled (+2)	Flexible (+2)	No end symm (+2)	No insert symm (+2) (+1) if clear	Heavy or tools (+2)	AL (+2)	OB (+2)	NTD (+2)	RES (+2)	HIP (+2)	FASTEN Twist (+1) Screw (+3)					
Aluminum Plate							2		2		2		2	12	0	3	6
Guide Rail					2		2				2		2	12	2	3	6
Bolts (attach plate to rail)				2			2						8	32	0	5	40
Nuts (attach plate to rail)	1					2	2		2			1	8	64	0	12	96
Cam Follower				2			2				2		2	12	2	3	6
Bolts (attach follower to rail)				2			2		2				8	48	0	5	40
Nuts (attach follower to rail)	1					2	2		2			1	8	64	0	12	96
Motor Axle Assembly																	
Flange Mounted Ball Bearings				2		2					2	3	2	18	2	8	16
Bolt (attach bearing to frame)				2			2						4	16	0	5	20
Nut (attach bearing to frame)	1					2	2		2			1	4	32	0	12	48
5/8 9-tooth Sprocket						2					2	3	2	14	2	8	16
5/8 Shaft									2				1	2	1	17	17
35-tooth Sprocket						2						3	1	5	1	8	8
Crank Axle Assembly																	
Flange Mounted Ball Bearings				2		2					2	3	2	18	2	8	16
Bolt (attach bearing to frame)				2			2		2				4	24	0	5	20
Nut (attach bearing to frame)	1					2	2		2			1	4	32	0	12	48
35-tooth Sprocket						2					2	3	1	7	1	8	8
5/8 Keyed Shaft									2				1	2	1	17	17
Front End Collar						2						3	1	5	0	19	19
Front Crank											2		1	2	1	3	3
Front Key	1						2						1	3	1	10	10
Back End Collar						2			2			3	1	7	0	19	19
Back Crank											2		1	2	1	3	3
Back Key	1						2						1	3	1	10	10

Part	Retrieve			Handle			Insert						# Parts	Assembly Index	Part Required	Time to Assemble a Fixture	Total Time for Fixtures
							AL = alignment difficult NTD = not top down HIP = hold in place			OB = obstructed RES = resistance							
	Small <12mm (+1) <2mm (+2)	Tangled (+2)	Flexible (+2)	No end symm (+2)	No insert symm (+2) (+1) if clear	Heavy or tools (+2)	AL (+2)	OB (+2)	NTD (+2)	RES (+2)	HIP (+2)	FASTEN Twist (+1) Screw (+3)					
Coupler Attachment																	
Bolt (attach crank to coupler)				2									2	4	2	5	10
Thrust Bearing									2				4	8	4	3	12
Thrust Bearing Washers													8		8	3	24
Coupler (rectangular steel bar) w/ press fitted bearing											2		2	4	2	3	6
Nut (attach crank to coupler)	1					2	2					1	2	12	0	12	24
Rocker Attachment																	
Flange Mounted Ball Bearings				2		2					2	3	4	36	4	8	32
Bolt (attach bearing to frame)				2			2						4	16	0	5	20
Nut (attach bearing to frame)	1					2	2	2	2			1	4	40	0	12	48
Shaft									2				2	4	2	17	34
Rocker					2						2		2	8	2	3	6
Collar						2						3	2	10	0	19	38
Thrust Bearing							2		2		2		4	24	4	3	12
Thrust Bearing Washers							2				2		8	32	8	3	24
Bolt (attach coupler to rocker)				2			2						2	8	2	5	10
Nut (attach coupler to rocker)	1					2	2		2			1	2	16	0	12	24
Motor/Chain Attachment																	
Motor				2	2	2	2						1	8	1	3	3
Screw (attach motor to frame)				2		2	2					3	4	36	0	2	8
Sprocket						2			2			3	1	7	1	8	8
Chain Tensor									2				1	2	0	3	3
Bolt (attach tensor to frame)				2			2					3	1	7	0	2	2
Chain			2				2	2	2	2			1	10	1	3	3

Part	Retrieve			Handle			Insert						# Parts	Assembly Index	Part Required	Time to Assemble a Fixture	Total Time for Fixtures
							AL = alignment difficult NTD = not top down HIP = hold in place			OB = obstructed RES = resistance							
	Small <12mm (+1) <2mm (+2)	Tangled (+2)	Flexible (+2)	No end symm (+2)	No insert symm (+2) (+1) if clear	Heavy or tools (+2)	AL (+2)	OB (+2)	NTD (+2)	RES (+2)	HIP (+2)	FASTEN Twist (+1) Screw (+3)					
Foot Pedal Attachment																	
Foot Carriage				2	2		2				2		2	16	2	3	6
Steel Ball Joint Rod Ends				2					2			3	4	28	4	10	40
Rod							2		2				2	8	2	17	34
Inside End Collar						2			2			3	2	14	0	19	38
Inside Collar						2			2			3	2	14	0	19	38
6 ft Square Steel Tube							2				2		2	8	2	3	6
Collar						2						3	2	10	0	19	38
Mounted Ball Bearings				2		2			2		2	3	2	22	2	8	16
Bolts (attach bearing to steel tube)				2			2		2				4	24	0	5	20
Nuts (attach bearing to steel tube)	1					2	2		2			1	4	32	0	12	48
Metal Block									2		2		2	8	0	3	6
Metal Sleeve							2		2		2		2	12	0	3	6
Bolt (connect tube to sleeve/block)				2			2		2				2	12	2	5	10
Nut (connect tube to sleeve/block)	1					2	2		2			1	2	16	0	12	24
Hitch Pins				2	2	2	2		2				2	20	0	17	34
Long Chain			2				2	2	2	2			1	10	1	3	3
Chain			2				2			2			1	6	1	3	3
SUM of Penalties	14	0	6	48	12	74	82	6	78	6	50	89					
												Total	218	1282	90		1831

Goal: minimize assembly index and parts count

Part required if: relative motion
different material
(dis)assembly impossible without

Parts reduction: 128