Spring 4-2014

Design of a Lean Manufacturing System for the Production of Compliant Wind at Sparton Electronics

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A Thesis Submitted to the College of Engineering Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Mechanical Engineering

Embry-Riddle Aeronautical University
Daytona Beach, Florida
April 2014

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Acknowledgement

I would like to thank my thesis advisor Dr. Patrick Currier for his help and guidance throughout this entire project. Without his support and meaningful insight I would not have been able to complete this thesis. I am also thankful to Dr. Sathya Gangadharan (a.k.a. Dr. G) for his continued support and encouragement.

I wish to express my genuine appreciation to Kevin Farthing at Sparton Electronics for his unlimited support, advice and patience.

Lastly, but most importantly, I would like to thank my family for always being there for me and motivating me. Without them, I would not have been able to get through graduate school.

Abstract

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Title: Design of a Lean Manufacturing System for the Production of Compliant Wind at Sparton Electronics

Institution: Embry-Riddle Aeronautical University

Degree: Master of Science in Mechanical Engineering

Year: 2014

Increased demands in production numbers and higher expectations for product quality in today's manufacturing industries have led to initiatives to improve processes through lean concepts. This study was conducted to demonstrate how Lean Manufacturing tools and techniques can be used to redesign a production system. The study focuses on the production of the compliant wind at Sparton Electronics. The compliant wind is one of the key components of a sonobuoy and its primary function is to isolate electrical components such as hydrophones from movement of the surface buoy. The goal of the redesign process is to increase production by focusing on customer demand. Quantitative tools, such as just-in-time production and takt time are used to design the tangible aspects of production. Qualitative tools, such as creating stability, standard work, and flow in production are used to control the intangible aspects.

To accomplish the goal of increasing production, this thesis proposes a machine and process that incorporate fundamental Lean Manufacturing concepts. The output is a redesigned manufacturing process and machine that, in theory, increases production by reducing cycle times and work in progress, establishes stability by creating standard work, and eliminates wastes such as wait time and unproductive movement.

The new manufacturing system has the ability to meet the customer demand in regards to units produced, and is also capable of increasing daily production by at least 15%. Additionally, utilizing modern components helps alleviate maintenance issues and increase equipment availability.

Table of Contents

List of Figures

List of Tables

List of Acronyms

SONAR	Sound Navigation And Ranging
TPS	Toyota Production System
JIT	Just-in-Time
WIP	Work In Progress
TPM	Total Productive Maintenance
OEE	Overall Equipment Effectiveness
RPS	Roller Pinion System
PF&D	Personal Fatigue and Delay

Chapter 1: Introduction

The objective of this thesis is to address the current manufacturing and production challenges of the compliant wind at Sparton Electronics. The compliant wind is one of the key components of a sonobuoy. Its primary function is to help separate the movement of above-water surface components, such as the antenna from below-surface components like the hydrophone. The compliant wind consists of a rubber bungee and conductor cable, with the cable wrapped around the rubber bungee cord. At Sparton, the compliant wind is produced by wrapping the conductor wire around a steel cable and then pulling the bungee through the wind. This process utilizes DC motors for wrapping and pulling and is handled by two operators.

Even though the overall quality of each compliant wind is acceptable, the engineering staff has to make adjustments constantly to address issues such as fluctuation in the pitch and diameter of the product. Additionally, due to most of the equipment being relatively outdated, the manufacturing process is interrupted for maintenance regularly. These issues along with high work in progress and cycle times contribute to low production numbers. In order to address the mentioned issues, lean concepts are used to pinpoint the source of each issue and also to redesign the current machine and manufacturing process.

1.1 Product and Company Background

Naval warfare during both World Wars played an important role not only in the result of each war but also in the history of the world. A key component of naval warfare was the submarines. With technological improvements of the submarines during the First World War, the need for an effective tracking system was born. The British originally invented the Sound Navigation and Ranging (SONAR) during World War One to meet this need, but the only way to detect submarines was by listening for them or encountering them visually while they were on the surface recharging their battery banks. It was not until World War Two when remote devices were needed in order to detect the more advanced German U-Boats. The proposed solution was to drop sonobuoys equipped with hydrophones and HF transmitters from convoy ships. These radio sonobuoys would then relay detection of a submarine to the convoy, alerting them of an attack. As a result of the joint war effort, the United States and United Kingdom started the development activities for the sonobuoy in the War Research Laboratory of Columbia University. Testing of sonobuoys started in March 1942 and, because of its success, by early 1943 the sonobuoy system became operational (Holler and Horbach et al, 2008).

In early 1950s, the manufacturing and production of sonobuoys for the United States Military was handled domestically. One of the major companies to manufacture the sonobuoys was the Sparton Corporation. Founded in 1900 by two brothers, Phillip and Winthrop Withington, Sparton Corporations was initially known as the Withington Company. A few years later, the brothers partnered with William Sparks and the name was changed to Sparks-Withington Company. In early 1900s the company mainly manufactured steel parts for the agriculture industry. With the evolution of the automotive industry in later years, the company started manufacturing car parts such as hub caps, brake drums and radiators. In the 1930s and 1940s, Sparks-Withington started producing radios and television components as well as other electronic parts.

It was not until the beginning of 1950s that disagreements between owners and shareholders resulted in a new group of investors taking over. The company's name was officially changed to Sparton Corporations in 1956. It was in the same year that Sparton made a risky decision to discontinue production of radios, televisions and most other electronic components to concentrate on military electronics business. This eventually led to the company experimenting with sonobuoys and manufacturing them a few years later (Anon, 1997)

Over the past 50 years, two companies, Sparton Corporations and Ultra Electronics – USSI, have handled the development and manufacturing of sonobuoys for the United States Navy. With Sparton Corporations receiving the larger portion of the most recent contract, the production of sonobuoys has ramped up in the company's DeLeon Springs, FL plant. The increase in production has directly affected operating hours, maintenance time, cycle times, quality control, and safety concerns throughout the entire manufacturing process.

The manufacturing of a sonobuoy involves several different processes due to the variety of components that are required for a complete product. Each sonobuoy consists of a hydrophone, battery pack, transmitter, and a flotation device. Figure 1 illustrates the main components of a sonobuoy.

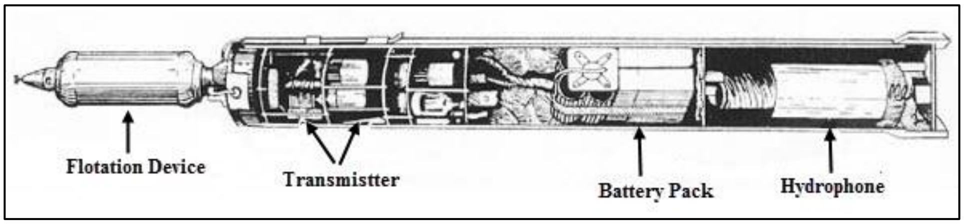

Figure 1 - Sonobuoy Components

Sonobuoys are ejected from aircrafts or ships in canisters and deploy upon impact with water. The flotation device keeps the transmitter and antenna above water while the rest of the sonobuoy descends below the surface to a selected depth. In order to isolate the hydrophone from movement of the surface flotation device, sonobuoys commonly use a rubber (compliant) suspension cable. This compliant cable contains the necessary electrical conductors. At Sparton, this component, which is a combination of a rubber bungee cord and electrical cable, is referred to as the compliant wind. Figure 2 (Rice, 1990) shows a deployed sonobuoy with the compliant cable and other auxiliary components.

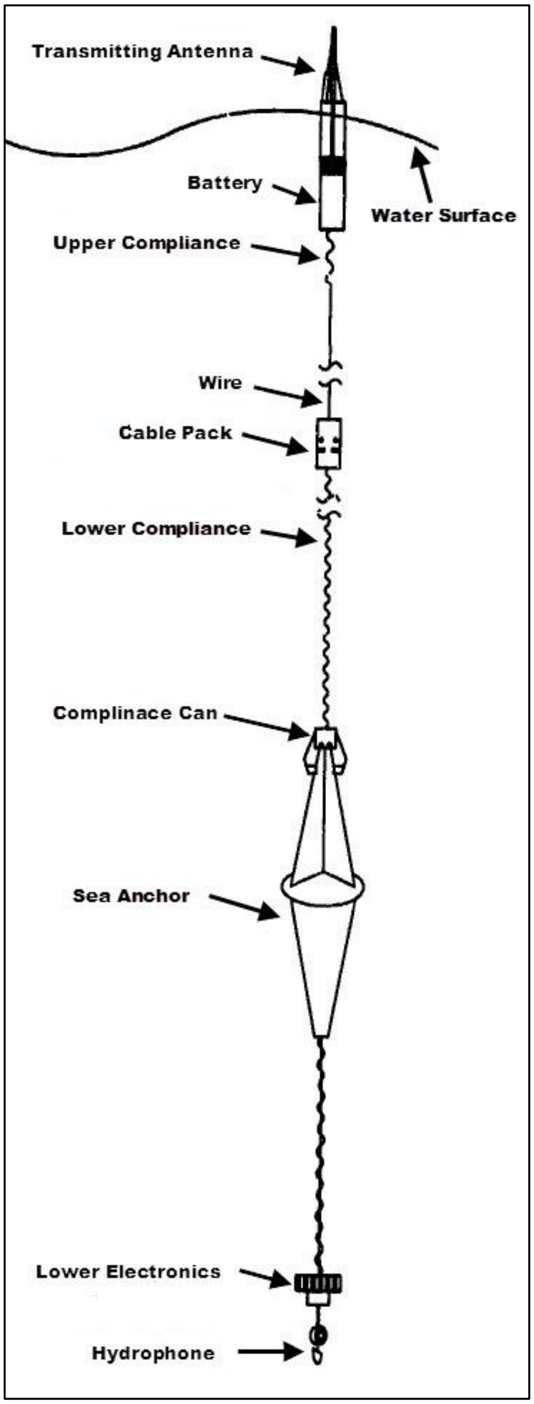

Figure 2 - Deployed Sonobuoy

The compliant wind (compliance) can be used in multiple areas in a sonobuoy. The main purpose of using such component is not only to isolate lower parts from the flotation device but also to provide flexibility for all under water components. This flexibility is extremely important due to the fact that ocean waters can be choppy and water movement can damage the sonobuoy components if they are connected to each via a solid object. The bungee (rubber) cord in a compliant wind helps alleviate these concerns. This thesis focuses on the production of the compliant suspension cables/compliant wind, which consists of wrapping conductor wire around a bungee cord.

1.2 Problem Statement and Objectives

Recent demands for increased production have put pressure on the manufacturing of the compliant wind. Though functional, the current manufacturing process is not fully effective and is facing several problems. The current process uses three independently controlled variable speed motor and brake combinations in conjunction with a rotating arm and a trolley system on a linear track to wind wire around a bungee cord. Due to the fact that each motor is controlled separately, the product's diameter and pitch fluctuate by up to 20% of the required dimensions within a single wind. To produce a quality wind each individual motor and brake need to be adjusted several times a day which not only results in inconsistent wind but also stops production and increases maintenance. In addition to problems regarding the wind consistency, the track and trolley system used to stretch the wind clutter the work surface and damage the wire and bungee cord. This also affects quality and increases safety concerns.

Yet another quality concern is related to the wrapping of the wire. The wire used for the wind is unwrapped by a flywheel/rotating arm from a spool, which rotates freely on a spindle. In order to un-wrap the wire from the spool and wind it around the steel mandrel cable, the large flywheel has to rotate at speeds above 1000 rpm. This rapid rotation and lack of balance in the assembly structure create excessive vibration, which in turn impacts the quality of the wind.

The current process also presents multiple safety and ergonomic issues. The cluttered work space may cause the operators to get hurt while moving or re-locating assembly parts such as the track and trolley. The operators have to lift a heavy cover to feed the wire through the winding mechanism for every new wind. In addition to lifting the cover, operators need to replace the empty spool with a new one multiple times a day. This means lifting a 20 lbs. spool every time the spool needs to be replaced.

In addition to the quality problems, there are multiple quantitative inefficiencies that exist in the current manufacturing process. These inefficiencies can be categorized as different types of waste; most importantly movement and waiting. The operators have to move quite often to perform certain tasks. This excess movement is not contributing any meaningful value to the end product. It is merely a necessity because of the way the current machine and process are set up.

The other significant problem is the amount of time an operator has to wait before starting the next cycle. The high work in progress (WIP) and cycle times are contributing to the operators having to wait a long time before taking action and starting the next process.

The availability of each assembly line as well as constant interruption due to breakdowns have also contributed to undesirable production numbers. Table 1 illustrates the number of breakdowns for a 4 month period (January 2013 – April 2013) and the average number of days a breakdown occurs.

Table 1 – Winder Downtime and Cost

Machine	Breakdown	Time Between Breakdowns (Days)
Machine #1	22	2.9
Machine #2	30	2.1
Machine #3	12	5.3
Machine #4	17	3.7

The average time between each breakdown is calculated based on a 4 day work week (64 total work days in a 4 month period). As it can be seen from Table 1, the number of breakdowns and the average time between each breakdown is significantly contributing to lack of equipment availability and is also creating interruptions in production. Because of these constant interruptions, flow is difficult to establish in the manufacturing process. This directly affects the number of compliant winds produced.

The primary objective of this thesis is to present solutions to increase the production of the compliant wind. This is achieved by analyzing the current manufacturing process and pinpointing its problems. With the production goal in mind, a solution is then presented for each individual problem. Throughout the entire design process, Lean Manufacturing concepts and tools are used to justify the changes. The new design endeavors to achieve the following:

- More accurately control the wind's diameter and pitch
- Reduce vibration caused by spindle and flywheel
- Reduce floor space usage
- Improve ergonomics and reduce safety concerns
- Reduce work in progress
- Reduce cycle times
- Increase assembly availability
- Reduce time spent on maintenance

1.3 Research Approach

To address the issues at hand with the production of the compliant wind, the current manufacturing process is assessed thoroughly. This assessment includes meeting with production managers and assembly line workers to determine flaws and inefficiencies in the process, as well as gathering data in regards to cycle times, work in progress, waiting time, etc. from the manufacturing process. Each problem area is then classified as either qualitative or quantitative in order to come up with the most appropriate method to resolve it.

In order to take a proven scientific approach for the design of the new manufacturing machine and process, Lean Manufacturing concepts are used. Lean techniques and tools are studied to better understand the history and how to effectively and systematically apply them to the production of the compliant wind. Some of these tools and techniques include using a pull system instead of push system, establishing a continuous flow in the process, minimizing movement, eliminating waiting time, decreasing cycle time, and synchronizing takt time to cycle time.

1.4 Thesis Outline

The remainder of this thesis outlines the research in regards to Lean Manufacturing concepts and how to apply them in the development of the new compliant wind manufacturing process. The chapters are as follows:

Chapter 2 provides a history of craft and mass production systems and how Lean Manufacturing was evolved. This chapter also defines lean and what tools and techniques are commonly used in Lean Manufacturing systems.

Chapter 3 assesses the current compliant wind manufacturing process and categorizes the deficiencies as quantitative or qualitative.

Chapter 4 discusses the new manufacturing design process, including details about the new machine, operator involvement, and assembly layout.

Chapter 5 examines the results and compares the current process with the new recommended process. The comparisons are between production numbers, cycle times, equipment efficiency, and several other factors.

Chapter 6 presents the conclusions and gives suggestions for future work.

Chapter 2: Background and Literature Review

In order to fully understand Lean Manufacturing and apply its concepts, a systematic study was done on its history as well as its most effective tools and techniques. Due to the fact that lean is a very broad topic and it covers not only the manufacturing aspect of a company but also the company's culture and its relationship with customers, vendors and employees, the study in this section is limited to the scope of applying lean methods to a manufacturing assembly line and how to increase production while eliminating waste.

2.1 History of Lean

In the late 1800s, Panhard et Levassor (P&L) was the only company in the entire world that built automobiles. Primarily a manufacturer of metal-cutting saws, P&L's main work force was composed of highly skilled crafts people who had complete understanding of an automobile's mechanical design principles. Each automobile was designed and built based on the Panhard System but due to different customer demands and lack of consistency across the entire process, each car was significantly different than the ones produced before.

It was not until 1908 that Henry Ford introduced the idea of mass production. The key to mass production was not just the moving assembly line but also the ability to completely and consistently interchanging parts. Ford was able to accomplish interchangeability by using the same gauging system throughout the entire manufacturing process. Advancement in machine tools also allowed parts to be produced more efficiently, eliminating the need for "skilled" workers who formed a large population of the labor force. In addition to accomplishing product consistency and reducing work force, Ford was able to create more efficiency by introducing the moving assembly line. The workers no longer had to move from station to station to perform tasks. Instead, the moving assembly line brought the car past stationary workers. This new innovation cut cycle times dramatically and increased production. By early 1920s, Ford's success was well documented and the magnitude of productivity improvement caught the attention of auto assemblers all around the world (Womack et al., 1990, pg. 21-25).

Despite two World Wars and many challenges in the economy, Ford remained the number one automaker in the world. Inspired by Ford's continued success and facing many production and sales challenges, the Toyota Company in Japan decided to take notes from its American counterpart. One of Toyota's brightest engineers, Eiji Toyoda, visited Ford's River Rouge Plant in Michigan during the early 1950s. He soon realized that mass production of that magnitude was inefficient for Toyota and impossible to replicate in Japan. Therefore, he decided to adopt the main mass production concepts and add a unique qualitative twist that made it work for Toyota (Womack et al., 1990)

Toyoda along with Taiichi Ohno, one of Toyota's chief engineers, carefully assessed every aspect of mass production and concluded that due to Japan's small domestic market, labor laws, and inability to purchase Western production because of the effects of World War II a new system had to be developed. This is when the Toyota Production System also known as TPS was born. The TPS focused on delivering quality products with the exact quantity needed at the right time. The two pillars of TPS, Just In Time (JIT) and *Jidoka*, not only laid the foundation for quality and quantity control, but they also defined what the culture within a production system should be. Additionally, Toyota's new system empowered its employees by giving them more responsibility and rewarding them with better wages and lifetime employment (Womack et al., 1990).

In his 1988 book, *Toyota Production System: Beyond Large-Scale Production*, Ohno makes three main statements that define TPS:

- "The basis of the Toyota Production System is the absolute elimination of waste." (pg.4)
- "Cost reduction is the goal." (pg.8)
- "After World War II, our main concern was how to produce high-quality goods. After 1955, however, the question became how to make the exact quantity needed." (pg. 33)

Toyota's way of thinking became the new stepping stone for all manufacturers to find success. In 1990, James Womack, Daniel Jones, and Daniel Roos coined the term "lean" in their book *The Machine that Changed the World*. The authors compared Toyota's Lean Manufacturing concepts to mass production and pointed the advantages and disadvantages of becoming lean. The book caught the attention of manufacturers and popularized the term "Lean Manufacturing" (Wilson, 2010).

2.2 Definition of Lean

Since its introduction in early 1990s, the term “lean” has been defined by many across all production related disciplines. At its core, lean and more specifically Lean Manufacturing is about doing more by using less. In manufacturing, doing more refers to increase in production, quality, efficiency, and many other aspects of creating a product from its initial design all the way to testing and delivery to the customer. On the other hand, using less refers to a decrease in all of the resources that go into creating a product such as time, space, human effort, machinery, and materials.

In order to do more and use less, one must assess every aspect of the entire manufacturing process and pinpoint the problem areas. The most convenient way to pinpoint problem areas is to find out what is producing waste. Most manufacturing processes can become more efficient by just eliminating wastes whether it is related to excess processing, waiting, defective parts, or overproduction. Even though the eventual goal of Lean Manufacturing is producing more with less, details of the tools by which that goal is achieved is extremely important. In the book *How to Implement Lean Manufacturing*, the author Lonnie Wilson states that Lean Manufacturing is a set of comprehensive tools and techniques that when combined and matured, will allow waste to be reduced which will not only make a production leaner, but it will also create flexibility and responsiveness (Wilson, 2010, pg. 9). To better understand how waste affects manufacturing and production, a list of the most common types of wastes are described in the next section.

2.3 Types of Waste

One of the most crucial contributions of the Toyota Production System (TPS) to the evolution of Lean Manufacturing was the recognition of the different types of waste that exist in a production system. Known as Muda in the Japanese culture, waste should be completely eliminated not just reduced (Ohno, 1988). To achieve a lean production system, one should define and recognize anything that may create waste.

Originated by the TPS and refined by many others, there are seven principle wastes that contribute to deficiency within a manufacturing system (Ohno, 1988).

Overproduction

Perhaps the largest of all wastes, overproduction refers to producing more than what is needed and is often driven by a "just in case" mentality. Making more products than what the demand requires not only leads to waste in storage and excess inventory, but it also contributes to other types of waste such as more processing time, handling of large batches, more defective parts, and many others.

Waiting

Waiting is any amount of time that the work-in-progress has either stopped or delayed. This can be short term or long term but the essence of this wait time is the fact that no value is being added to the production. Waiting can happen due to broken machinery, shortage of material, or an unbalanced assembly line which allows pockets of time to be wasted without any valuable work to be done.

Transportation

This waste occurs when parts have to be moved. Whether this happens when processing steps, processing lines, moving products from one area to another or shipping products to the customer, transportation and handling of parts can create larges wastes. One may argue that transportation is an inevitable waste but the reality is that there are several aspects of this type of waste that can be minimized if not completely eliminated.

Excess Processing

When a product is processed beyond what is needed and what the customer demands, this waste occurs. Excess or over processing often starts at the design stage of a manufacturing process when poor and inefficient processing equipment is selected. This results in an unnecessary waste in time and energy when the product is being manufactured.

Movement

In a production line movement has two main elements; human and machine. The waste from the human element is driven from ergonomic factor and it can be from excess walking, reaching, and twisting. These not only contribute to productivity and quality but also create safety issues. The waste from the machine element can occur when equipment is positioned unnecessarily far from a worker or if a worker's interaction with the machine is taking longer than it should because of the way the machine is designed. These elements result in low productivity, bad quality, and workers who are in danger of getting hurt. The waste in movement should be considered as an important factor when designing a manufacturing machine/process.

Inventory

Any raw material, work in progress, or finished good is considered inventory. If inventory is managed based on material requirements and not production requirements, there will be a considerable amount of waste. The key to inventory is its translation to sales. Any inventory is considered waste if it does not directly protect sales.

Defective Parts

This refers to the product that is considered scrap or needs extra work to be corrected. Any manufacturing machine or process that ends up producing defective parts not only creates problems in quality of the product, but it also wastes the energy, time, and effort which were put into building the product.

2.4 Lean Manufacturing Tools and Techniques

The most fundamental Lean Manufacturing tools and techniques are adopted from the very basic concepts of the Toyota Production System. At its core, TPS is a quantity control system but the culture at Toyota and the appropriate implementation of quantity control tactics allow quality control to fall in place seamlessly (Wilson, 2010).

Figure 3 (Liker, 2003) illustrates the two pillars of TPS, Just-in-Time (JIT) and Jidoka, and the philosophy used to achieve waste reduction. The first pillar, JIT, refers to producing the right item at the right time and at the right quantity. Unlike most conventional mass production systems that employ a "just-in-case" mentality irrespective of actual customer demand, JIT is strictly based on the quantity needed by the customer (Dennis, 2007, pg.67). This in turn results in an efficient system with minimized "safety net". Because of this minimized buffer, the timely quality inspection of each product becomes crucial. This is when the second TPS pillar, Jidoka, comes into play. Jidoka is a set of inspection techniques that prevent defective parts from moving along the assembly line. In addition to defective parts, any other problem that may contribute to decreasing the quality of the product has to be addressed immediately either by shutting down the entire manufacturing process or by creating warning signs such as buzzers or lights.

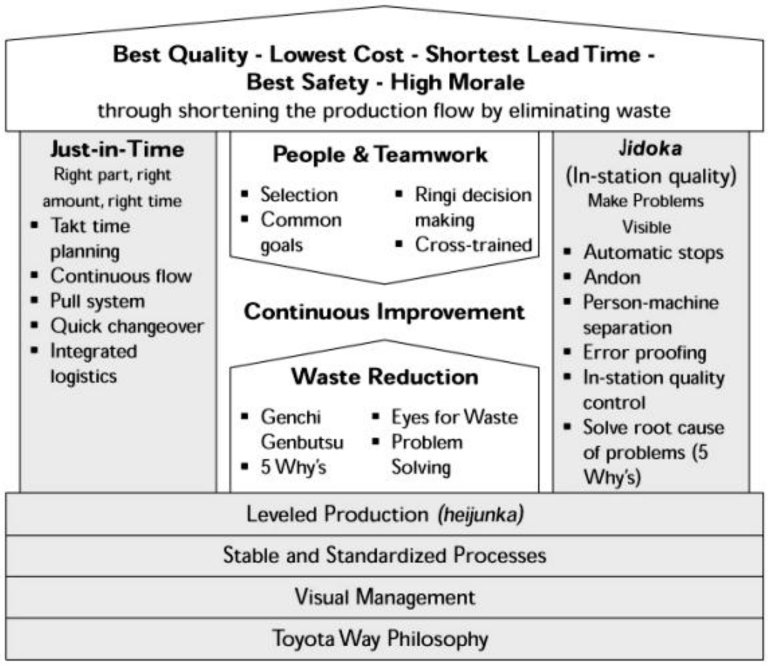

Figure 3 - Toyota Production System

2.4.1 Quality Control Techniques

Even though most production systems are quantity driven, the importance of quality control cannot be underestimated. The main two strategies of quality control are proper handling of the workforce and stabilizing all processes to meet customer demand. These strategies are explained in detail below.

2.4.1.1 Workforce

Workforce is the human element in manufacturing. In recent years, automation has decreased the role of human workforce, but due to complex manufacturing needs and cost of automation, this role has remained a crucial part of most production systems. Therefore, the strategy should be to empower the workforce by giving each worker more responsibility and ensure thorough training is performed.

People

People are the essence of any production system. Individuals who work in an assembly line are the ones that know the most about how a product is built. They are involved in each step of the manufacturing process and in most cases are the only ones to add value to the finished product. Successful companies like Toyota that truly understand the value of people are not only concerned with proper training but also with the workers' career planning and commitment to their job. This creates a culture in which workers feel included in the company's mission and are willing to accept more responsibility because they have been given the assurance that they matter (Feld, 2001, pg. 32).

Multi-Talented Workers

The willingness to accept responsibility opens up more opportunities for everyone. The workers can now be trained in different areas and the company can use these multi-talented individuals in different parts of an assembly line. This also adds more flexibility to the production system and creates an environment in which lean principles can be effectively implemented.

Problem Solving by All

Another aspect of increased responsibility is problem solving by everyone starting with assembly workers. In a lean system, assembly workers are expected to solve simple problems without the involvement of managers or engineers. In a traditional mas production system however, problems may be seen as a sign of failure and are often hidden or shrunk away. TPS made it a point to create a culture that views problems as an opportunity to improve the system. Therefore, problems in a true lean system should be regarded as chance to eliminate weakness and become more robust and not the opposite (Wilson, 2010).

2.4.1.2 Stability

The second strategy in quality control is the stability of the entire manufacturing system and it impossible to achieve without stability in the 4 Ms; Man/woman, Machine, Material, and Method (Dennis, 2002, pg. 29). Stability of a system can be measured by Overall Equipment Effectiveness (OEE) and is achieved through specific techniques such as establishing consistent equipment availability, creating standard work, reducing cycle times, implementing 5S, being transparent, and performing Total Equipment Maintenance (TPM). These concepts are explained below.

Overall Equipment Effectiveness

One of the most common techniques to measure equipment's performance and production results is Overall Equipment Effectiveness (OEE). OEE is the product of three main operational parameters (Wilson, 2010):

- Equipment availability: total production uptime divided by total production planned uptime.
- Quality Yield: total salable units/products divided by total units produced.
- Cycle-time performance: total produced units divided by the volume that should have been produced during actual uptime at the design cycle time.

To following is an example of calculating OEE.

- Total production uptime is 8.5 hours (this includes lunch and breaks plus planned preventative maintenance) and total production planned uptime is 10 hours.
  - Availability (A) = 8.5/10 = 0.85
- Actual units produced is 150 with 5 rejects. This yields 145 salable units.
  - Quality Yield (Q) = 145/150 = 0.967
- Total produced units is 150, and the actual uptime is 8.5 hours. The cycle time for producing one unit is 180 seconds.
  - Cycle-time performance (P) = $150/[8.5 \times (3600/180)] = 0.882$
- OEE = $A \times Q \times P = 0.85 \times 0.967 \times 0.882 = 0.725$

The OEE for this production is 72.5%. More importantly using this metric, one can pinpoint the weakness in each area. In this example loses are as follows:

Availability losses = 15%

Quality losses = 3.3%

Performance losses = 11.8%

The data indicates that the main issues in this production system are the availability of the equipment and the losses due to performance. Increasing the actual equipment uptime can solve the availability problem. On the other hand, decreasing the cycle time can minimize performance losses.

Availability

The availability of a production system plays an important role in the stability of the entire process. High process availability is one of the major requirements of a lean system. Without consistent availability the production is interrupted and with each interruption whether it is due to machine downtime, equipment failure, or inability to deliver material to the production line, the process needs to be stopped and then restarted, resulting in creation of waste.

Cycle Time Reduction

Reducing cycle times throughout the manufacturing process is a technique that can be used for any production system, lean or not. Analyzing every step of the manufacturing process and finding gaps that do not add any value to the production can achieve cycle time reduction. These gaps may be due to operators waiting, unnecessary operator or machine movement, unsynchronized equipment, etc.

Standard Work

According to Ohno standard work has three main elements (Ohno, 1988):

- Cycle time
- Work sequence
- Standard inventory

Each element helps define a specific aspect of the “work” that needs to be done in order to accomplish the production goal. Overall, standard work forms a baseline for all activities, which can be used for further improvement. Each element of standard work must be clearly defined and visually displayed. This helps eliminate confusion and variation within a production line and contributes to the never-ending process of improving.

Transparency

Transparency is the concept of being able to "see", in real time what is happening in the production process (Wilson, 2010). Ideally, a manager should be able to determine within a few minutes whether a certain process is performing as designed. This concept goes hand in hand with standard work. Visually displaying the standard work makes the process transparent and helps everyone quickly understand it.

Total Productive Maintenance

One of the most important aspects of stability is the availability of the equipment that contributes to production. OEE metrics in most manufacturing plants indicate that availability is the largest source of process loss (Wilson, 2010). Inventors of the TPS realized this early and developed a set of activities to maximize equipment effectiveness by involving everyone. These activities were a series of small, systematic maintenance goals that when combined resulted in large improvements. In today's Lean Manufacturing, these activities are known as Total Productive Maintenance (TPM). The primary goal of TPM is to increase productivity by modest, yet effective investment in maintenance. Figure 4 (Kumar, 2008) illustrates the eight activities that make up TPM and 5S as its supporting foundation.

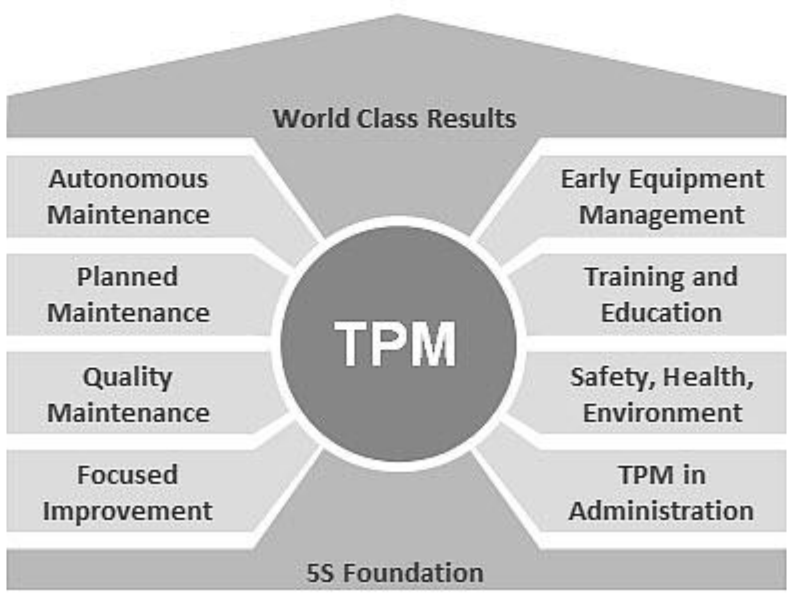

Figure 4 - Total Productive Maintenance

5S

Visual management of a workplace creates an environment, which is self-explaining, self-ordering, and self-improving. As mentioned earlier, standard work needs to be visually displayed in order to create transparency throughout a manufacturing plant. Similarly, 5S is a set of techniques, all beginning with the letter “S”, that is designed to create a visual workplace (Dennis, 2002, pg. 31). These techniques are:

- Sort: sort out what is needed and what is not. Anything that is cluttering the workspace and is not adding any value to production needs to be removed from the facility.
- Set in Order: after everything has been sorted out, the remaining components need to be organized efficiently to minimize wasted motion. These components may be machines, tools, storage shelves, etc.
- Shine: once things are set in order, it is important to keep the work place clean. A clean, organized work place helps boost employee morale and makes maintenance much simpler.
- Standardize: in order to ensure S1 through S3 are regularly repeated, standards need to be developed. These standards need to be visual and specific.
- Sustain: the last 5S technique is sustaining the work ethic by involving everyone to establish a sense of entitlement. This can be achieved by promotions, communication, and training.

2.4.2 Quantity Control Techniques

The activities and techniques in quality control are designed to create an efficient working environment and compliment the quality aspect of manufacturing. Due to the fact that quantity is directly related to profit, and every company’s goal is to increase profit, controlling quantity becomes extremely crucial. Every manufacturing/production process needs a deliberate quantity control system in order to properly handle all productions. TPS is the most successful model of a quantity control system. According to the TPS model, quantity control has two pillars; just in time (JIT) and jidoka. Each concept and its techniques are explained below.

2.4.2.1 Just in Time

Just in time (JIT) is a philosophy in manufacturing that involves having right parts needed in assembly reach the assembly line at the time they are needed and only in the amount needed (Ohno, 1988, pg. 4). The aim of this philosophy is to eliminate waste and better manage inventory. In most mass production systems inventory is managed based on projected customer demand. JIT is the complete opposite of such strategy in a sense that inventory is managed strictly based on the quantity needed by the customer. Through elimination of waste and timely management of inventory, JIT helps optimize all company resources such as capital, equipment, and workforce.

While the JIT philosophy is a great way to handle inventory and eliminate waste, it requires the involvement of everyone in a production system and true dedication for it to work. The JIT techniques provide a guide on how to go about employing the philosophy.

Takt Time

Takt time is derived from the German word Taktzeit, meaning meter. In Lean Manufacturing, takt time is best known as pace or rhythm of production. Takt time represents the process or cell cycle time based on customer demand and is calculated by taking the ratio of time available to produce and the quantity demanded by the customer (Feld, 2001, pg.69-70).

$$Takt\ Time = \frac{Available\ work\ time}{Customer\ demand}$$

Takt time is often associated with cycle time but it is calculated from a complete different perspective. The distinct difference between takt time and cycle time is expectation versus capability. While cycle time represents a cell’s or a process’ capability of the existing production takt time is based on the quantity needed by the customer, regardless of ability of the current process. If a system is designed to produce at a cycle time higher than takt time, meaning the process takes longer than what it ideally should, the production numbers will not meet the customer demand. On the other hand, if cycle time is lower than takt time, production numbers will be higher than customer need. Both scenarios lead to different types of wastes. Therefore, cycle time and takt time need to be synchronized to avoid underperforming or over producing.

The example below is given to better define takt time.

A company runs one 10-hour shift with 1-hour lunch break and two 15-minute breaks to produce snow shovels. The requirement from customer is to have 1000 shovels per day.

The first step to calculate takt time is to consider the actual availability of the production. In this example, it is 10 hours minus 1.5 hours for lunch and breaks, giving an 8.5-hour availability. Since the customer demand is 1000 shovels per day, dividing 8.5 hours by 1000 gives roughly 31 seconds. To stay in step with customer demand, one shovel needs to be produced every 31 seconds. However, since other losses such as maintenance and equipment failure can affct the production, overall equipment effectiveness also needs to be considered. If the OEE for the process is 0.85, the actual cycle time needs to be 26 seconds (0.85×31 seconds).

Cycle Time

Cycle time refers to the total time it takes for one unit to be produced. This includes, set up time, processing time, waiting time, and other delays that may occur during production. Cycle time can be calculated with the following formula (Rother et al., 2008):

Cycle Time = set up time + processing time + waiting time + moving time + inspection time + rework time + other delays

Pull Production

Similar to takt time, pull production technique is also customer focused and is a part of the just in time mentality. In a pull system, no products or services are produced until the customer asks for them (Dennis, 2002, pg. 71). This concept can be better explained through the following example. An individual damages the bumper on his car. He goes to his car dealer replace the bumper. The dealer provides the bumper and installs it. At this time, a "hole" is created in the dealer's inventory. This generates a signal in the local distribution center to send the dealer another bumper to fill the gap. The local distribution center supplies the dealer with the bumper and signals upstream to the main parts redistribution center. The main parts redistribution center provides the bumper and then signals the bumper manufacturer to build a new bumper. The bumper manufacturer schedules s lot of production time to make the bumper. This scenario shows how a pull production can work. Instead of the dealer and the parts distribution centers having to carry large parts stores and warehouses for their inventory, parts/products are manufactured based on customer's need. The pull system helps alleviate dealing with unnecessary inventory space where parts are difficult to track and shipping can take longer than normal. Figure 5 (Dennis, 2002, pg.72) illustrates the three loops explained in the pull production example.

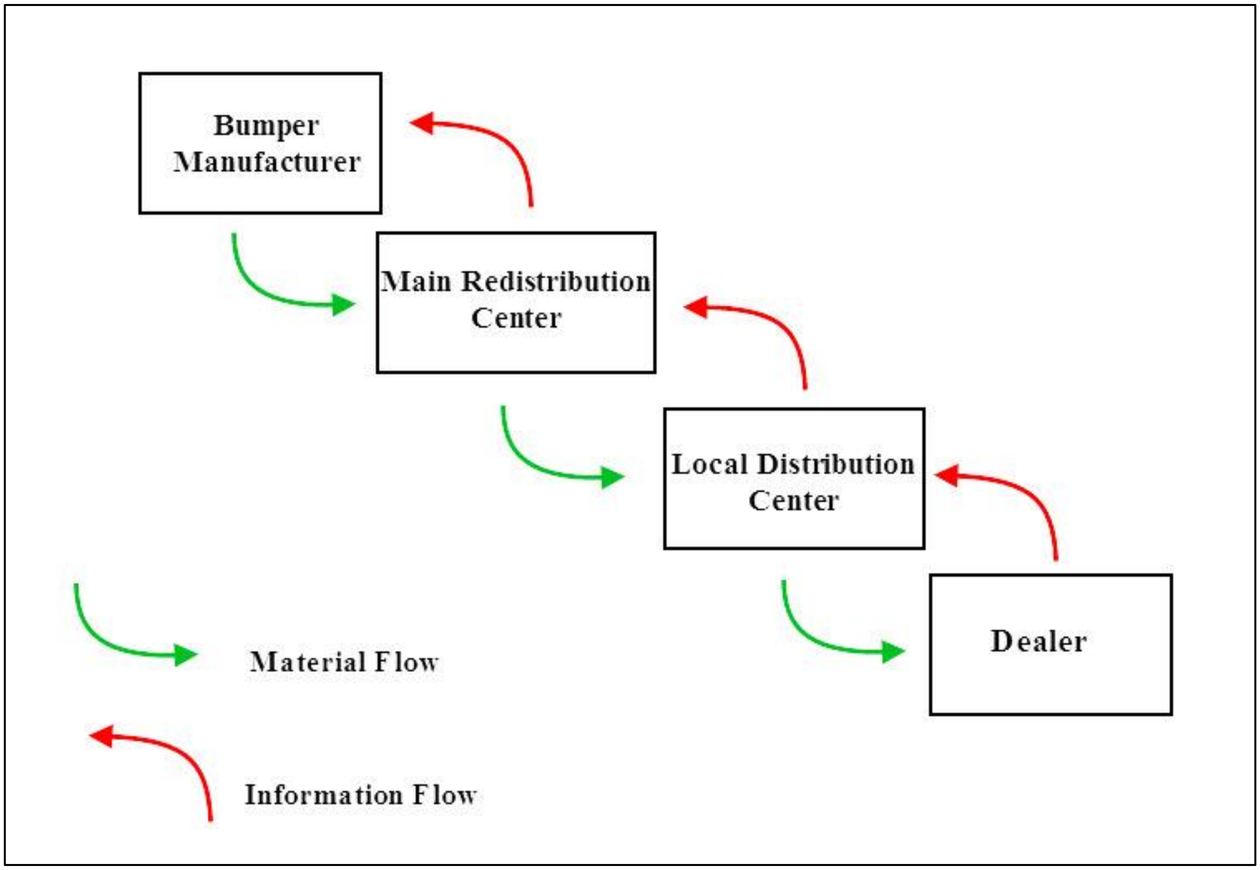

Figure 5 - Pull Production Flow Chart

Flow

Flow is the concept of parts and subassemblies constantly moving throughout the production system. The only stops are when a part or subassembly needs to be processed which is value added to the product (Wilson, 2010, pg. 67). The ideal process for incorporating flow involves having as little inventory as possible at each workstation and designing the process layout in way that all work stations are close to each other. This would help create one-piece flow with 100 percent value added. Even though the concept of flow is more an ideal than reality, the implementation of ideas that resemble flow is very possible.

Kanban

Kanban is a visual tool that streamlines communication regarding parts, products, inventory, pick-ups, transfers, etc. A kanban is usually a rectangular card in a vinyl envelope. The use of such system was popularized by TPS and even to this day is used by Toyota as its operating method. The main advantages of using a kanban are the ability to control inventory (since every part has to have a kanban), minimizing overproduction, and facilitating flow. For a kanban system to work, the rules of the system need to be followed religiously. Taiichi Ohno defined the main six functions of kanban along with its six rules. Table 2 illustrates these functions and rules (Ohno, 1988, pg.30).

Table 2 - Functions and Rules of Kanban

Functions of Kanban	Rules for use
Provides pick-up or transport information	Later process picks up the number of items indicated by the kanban at the earlier process
Provides production information	Earlier process produces items in the quantity and sequence indicated by the kanban
Prevents overproduction and excessive transport	No items are made or transported without a kanban
Serves as a work order attached to goods	Always attach a kanban to the goods
Prevents defective products by identifying the process making the defectives	Defective products are not sent on to the subsequent process. The result is 100% defect-free goods.
Reveals existing problems and maintains inventory control	Reducing the number of kanban increases their sensitivity

2.4.2.2 Jidoka

Jidoka is an inspection method that helps identify defects and eliminate them before advancing to the next phase. Jidoka is a Japanese word that is comprised of three Chinese words; *Ji, Do, Ka*. *Ji* refers to the worker. If the worker believes that he/she is creating defective parts or something is wrong with the process, the line must be stopped. *Do* refers to the motion or work and *Ka* is a suffix for "-ation". The word as a whole has been defined as "automation with a human mind" (Dennis, 2002, pg. 95). This implies being proactive about defects and errors and taking immediate counter-measures to eliminate them.

Any operation or system that requires the involvement of humans is bound to have errors. In fact, humans are the least reliable component in most complex system. To help minimize these inevitable errors, jidoka techniques are used.

Poka-yoke

From the Japanese words *Poka*, meaning error or mistakes, and *yoke*, meaning prevention, Poka-yoke is a series of techniques used to eliminate product defects by preventing, correcting, and drawing attention to human error as they occur. Since human error is a very realistic possibility, focusing on mistake proofing and preventing those errors before they result in defective parts is the key. Poka-yoke could be as simple as a checklist for an operator or as complex as sensors to detect weight, dimension, and shape of an object. The two main goals of poka-yoke are to carry out 100 percent inspection and provide immediate feedback and action to counter the error (Feld, 2001, pg. 85)

5 Whys

Another technique that can be quite effective for eliminating defects and quality inspection is 5 Whys. This simple technique does not require set up or cost to build. It is simply a series of five questions starting with the word "why" to uncover the root of a problem. The following example is the 5 Whys for a machine that stopped working (Ohno, 1998, pg. 17)

1. *Why* did the machine stop?
   There was an overload and the fuse blew.
2. *Why* was there an overload?
   The bearing was not sufficiently lubricated.
3. *Why* was it not lubricated sufficiently?
   The lubrication pump was not pumping sufficiently.
4. *Why* was it not pumping sufficiently?
   That shaft of the pump was worn and rattling.
5. *Why* was the shaft worn out?
   There was no strainer attached and metal scrap got in.

Repeating *why* five times in this example helped determine the underlying issue. Without this exercise, the fuse would have been replaced not realizing that the main problem was the strainer not being attached. The 5 Whys technique is very useful for all types of troubleshooting and it can be used to get to the bottom of an issue.

Kaizen

Kaizen is the concept of improving a process by performing a series of small continuous steps. The basic idea behind kaizen is that several small, continuous improvements are far more effective in an organizational environment than few large improvements. These small improvements affect processes more directly and over time contribute to the overall efficiency.

2.5 Reconfigurability

Quality and Quantity control are important aspects of production within a manufacturing process. However, a true Lean Manufacturing system is not solely based on what goes on with the product and how to manage its quality and quantity. In today's competitive manufacturing world, production systems need to be highly responsive and allow launch of new product models to be undertaken quickly. Production systems also need to be flexible enough to allow rapid integration of new functions and processes into existing systems (Mehrabi et al, 2000). Designing a manufacturing process where components are flexible and reconfigurable can help minimize changeover times and cause the least amount of interruption when change is needed. Reconfiguration in manufacturing includes several different aspects. Figure 6 shows these aspects.

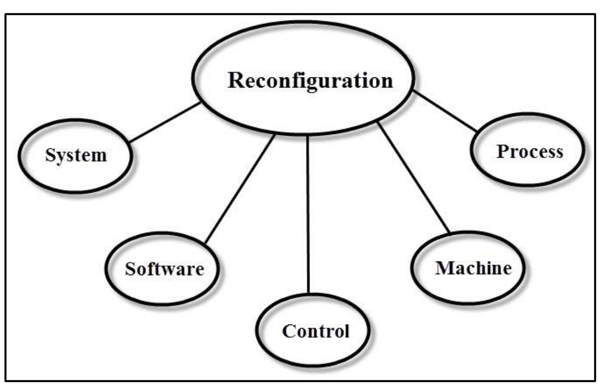

Figure 6 - Aspects of Reconfiguration

2.6 Maintainability

One of the requirements of a lean production system is the maintainability factor. As discussed in earlier sections, TPS uses a system called Total Productive Maintenance. Even though this system is a thorough, bottom-up approach it requires many cultural changes which are not quite feasible in certain production systems. Instead, to achieve lean from the maintainability stand point, the design of a manufacturing system needs to be modular. A modular design would allow components to be easily replaced and maintained. Due to the simplicity of such design, the need for complex parts is eliminated and maintenance is standardized. Most modular designs use bolt on connections along with slotted structures that make it easy to put together and take apart. Replacement parts are mostly standard parts which are readily available.

2.7 Ease of Access

The success of maintainability is mostly based on ease of access. Systems that are designed to have easy to access components can make the work environment more efficient for not only the maintenance staff, but also the operators. The positioning of components is an important factor in creating a machine or assembly line that has good access. Frequently serviced components such as motors, gears, controls systems, parts that need lubrication, etc. need to located in an area that does not create interference with production. This way the maintenance staff or engineers who have to service those components do not have to interrupt the production flow. Systems with good ease of access also help minimize ergonomic issues.

2.8 Ergonomics

The ergonomics factor in a manufacturing system refers to the physical engagement of the human element with production process and designing a system that is human centered. Because all human beings have physiological differences in height, weight, gender, and age the physical engagement with a system can vary. Any work performed within those physiological parameters will result in lower fatigue. On the other hand, work performed outside those boundaries will result in more fatigue and stress which in turn will affect performance and production.

Ergonomics in a Lean Manufacturing environment is one of the key factors in alleviating the waste related to the workforce. To prevent human fatigue and stress that can lead to injuries the following ergonomic principles need to be incorporated in the design of a process and also in everyday operations (Walder et al, 2007):

- Avoiding prolonged, static postures
- Promoting use of neutral joint postures
- Locating work, parts, tools, and controls at optimal anthropometric locations
- Providing adjustable workstations and a variety of tool sizes
- When appropriate, providing adjustable seating, arm rests, back rests, and foot rests
- Utilizing feet and legs, in addition to hands and arms
- Using gravity
- Conserving momentum in body motions
- Providing strategic location for lifting, lowering, and releasing loads
- Accommodating for a broad variety of workers with respect to size, strength, and cognitive abilities

Chapter 3: Compliant Wind Manufacturing Process

3.1 Manufacturing Process

The current manufacturing process of the Sparton Compliant Wind was analyzed by making several on-site visits to the company's DeLeon Springs plant. The company utilizes four assembly lines/stations with each line using a machine called the Compliant Winder to produce the product. Ideally, each assembly line requires at least two operators, one at each end of the line. While one operator is in charge of starting the process, the other operator waits for the machine to complete its cycle. Once stopped, the operator takes the necessary steps to create the wind. Figure 7 shows a diagram of the four assembly lines.

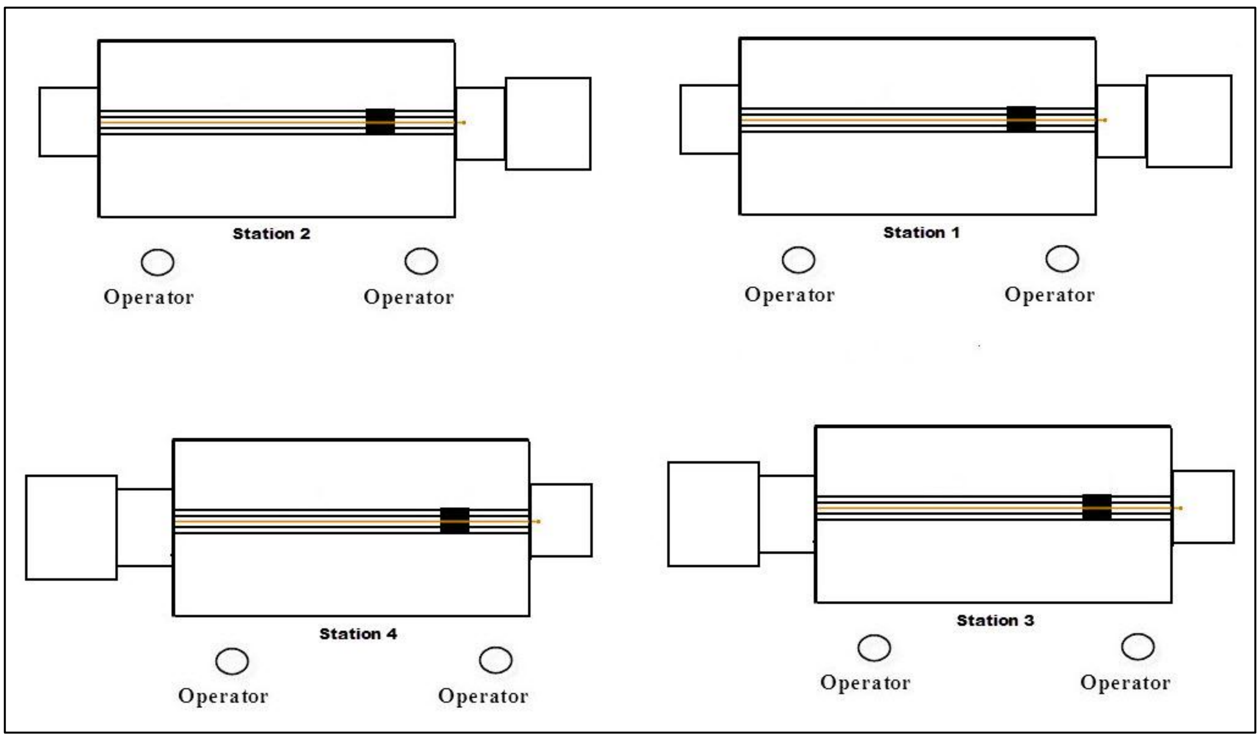

Figure 7 - Production Layout

The primary task of the machine in each station is to wind conductor wire around a mandrel cable. Once the wind is performed, the bungee is pulled through the wind. Figure 8 shows the finished product.

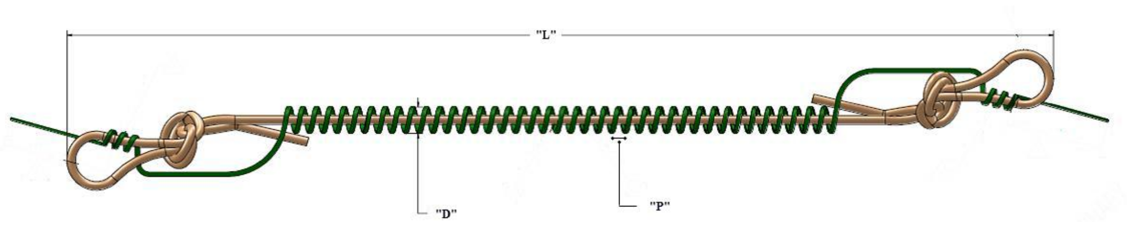

Figure 8 - Compliant Wind

L: Length of the bungee cord (192 +/- 12 inch length of longest cord)

D: Outside diameter of the wind (0.35" maximum)

P: Wind pitch (minimum of 50 coils per foot of wind)

3.2 Machine Components

Table 3 lists all machine components as well as each component's function.

Table 3 - Machine Components and Functions

Component	Function(s)
Headstock Motor	- Provides tension for the mandrel cable - Pulls the mandrel cable and bungee back through the wind
Tailstock Motor	- Pulls the wind and the mandrel cable as the compliant is wound
Wind Motor	- Rotates the wind mechanism (arm) around the spool of wire to perform the wind
Electric Brake	- Controls wind mechanism's number of rotations
Speed Controller	- Controls the speed of the wind mechanism
Guiding Wheels	- Spreads the winds as they are produced
Mandrel Cable	- Allows the wire to take its shape when winding mechanism wraps wire around it
Pull Cable	- Serves as a tool to pull the mandrel cable as well as the trolley from one end to another
Trolley	- Guides the mandrel cable and pull cable as they get pulled by the tailstock
"Dog Bone"	- Provides the connection between the mandrel and the pull cable - Releases the tension at the end of the wire

3.3 Assembly Layout

The layout of the assembly is simply a line and the entire process takes place on the "working" table. The headstock and winding motors are at one end of the line. The next section is a long table that the track and trolley are placed on. This table also serves as the working area for the operators. The pull motor also known as the tailstock is at the other end of the assembly line. Figure 9 shows the assembly layout.

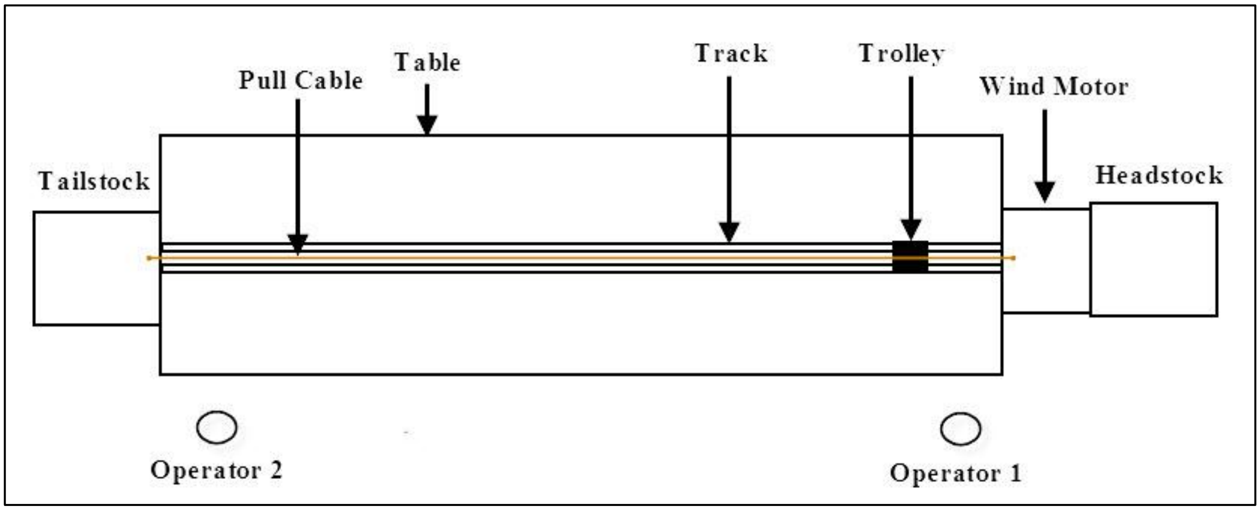

Figure 9 - Assembly Layout

Nearly 600 square feet of floor space is consumed as each assembly is over 37 feet long. Due to the length of the product and the type of material it is made out of, this type of layout appears to be the most efficient. However, recently Sparton has had to manufacture compliant winds that are different lengths. This layout is designed for the longest compliant wind and is lacking the dynamic ability to produce shorter products.

3.4 Overall Process Details

The manufacturing of the compliant wind consists of the following:

- The wind is produced by rotating an “arm” around a coated steel mandrel cable. The rotation of the arm unwraps conductor wire from a spool and winds it around the cable. A DC motor powers this mechanism and an electric brake controls the rotation. The speed of the wind is controlled via a discrete speed controller.
- To start the process operator lifts the spool cover, feeds the wire through the rotating arm and connects the wire to a trolley (guiding mechanism).
- The operator then closes the spool cover and starts the machine.
- As the wind is produced, the wind (wrapped wire) and the mandrel cable are pulled together by a pull motor and cable with a level wind flywheel in the tailstock. The wind is guided via a sliding trolley in a double “V” groove track.
- The tension of the mandrel cable is provided by a brake on the headstock motor.
- When the wind reaches the pre-determined length, the wind stops automatically and the operator disconnects the pull cable from the mandrel cable.
- The rubber bungee is then connected to the mandrel cable and the operator activates the headstock motor to pull the bungee through the wind using the mandrel cable.
- Next the operator activates the tailstock to reverse the motor and feed the pull cable back to the headstock.
- The operator then cuts the cable, ties the bungee ends, and makes the manual wraps on each end to complete the product.
- The process is then repeated after the operator lifts the cover and feeds the wire to the arm and the trolley.

3.5 Operator Involvement

The manufacturing of the compliant wind requires several specific tasks to be completed that at the current stage can only be performed by an operator. Each assembly line is handled by two operators with each operator standing at one end of the line. While the first operator is in charge of initiating the process, the second operator is tasked with completing the steps needed to finish the product. Table 4 lists the work elements needed to produce the compliant wind.

Table 4 - Current Process Work Elements

Step #	Work Element	Performed By
1	Spool cover is lifted	Operator 1
2	Wire is fed to a probe	Operator 1
3	Machine is started and wire is held	Operator 1
4	Wind is performed	Machine
5	Probe is unhooked	Operator 2
6	Bungee is connected to mandrel	Operator 2
7	Pull wire is triggered	Operator 2
8	Bungee ends are tied	Operator 1 & 2

Each operator performs the tasks that are on his/her side of the assembly. For example, the operator who is standing by the wind machine and spool (Operator 1) is in charge of lifting the spool cover, feeding the wire to a probe, and starting the machine. On the other hand, operator who stands at the end of the assembly line (Operator 2) is tasked with unhooking the probe, connecting the bungee to a mandrel cable, and pulling the trigger wire in order for the machine to pull the bungee through the wind. Each operator then ties one end.

The main issues with this process are lack of standard work and the amount of time each operator spends waiting on the machine. The tasks performed by operator 1 are much different than tasks performed by operator 2 and observing the process several times for hours at a time indicated that the duties of each operator are rarely rotated. This lack of standard work contributes to operators not having a balanced workload which in turn results in inefficiencies in the manufacturing process. The problem with operators waiting is a direct result of the machinery. Operators have no choice but to wait for the machine to finish its task. This issue is addressed more in detail in the next section.

Besides production issues, the current involvement of the operators with the machine presents some ergonomic problems. The operators have to replace the wire spool multiple times a day. A full spool weighs 25 pounds and in order to replace the spool the operator has to lift the spool above the working table. The table is slightly below most operators' shoulder height. Therefore, to replace the spool operators have to extend and raise their arms past their shoulder height. According to the Department of Labor and Industries, 25 pounds is well above the acceptable lifting range, considering that most operators at Sparton Electronics are females. Figure 10 illustrates the lifting guidelines for men and women (Triggs, 2006)

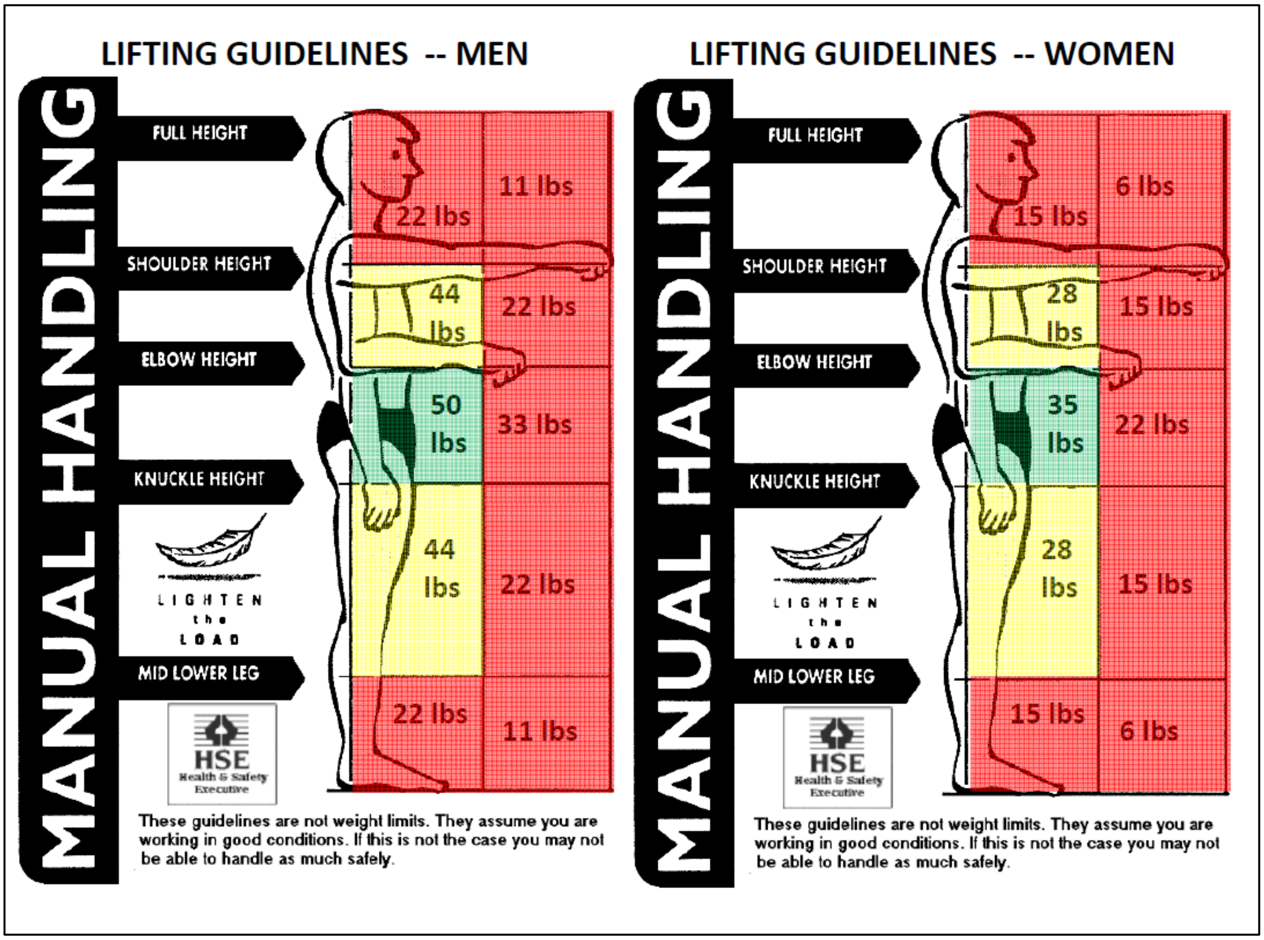

Figure 10 - Lifting Guidelines

3.6 Quantitative and Qualitative Measures

Similar to the study done in the background section, the tools and techniques of Lean Manufacturing can be better understood and implemented once they are categorized by aspects that can be counted (quantitative), and aspects that cannot necessarily be represented by numbers (qualitative).

In order to calculate the quantitative and qualitative measures associated with production of the compliant wind and how they affect the manufacturing process, certain assumptions and parameters are considered. These assumptions and parameters include:

- End customer is considered to be the next department/team that preforms the next set of operations to incorporate the compliant wind into sonobuoys.
- The daily customer demand is 600 compliant winds.
- The product is manufactured during one shift at four stations. This shift starts at 6am and ends at 4pm, with a one hour lunch break and two 15 minute breaks. Therefore, total planned uptime for the equipment is 34 hours.

3.6.1 Cycle Time

As stated previously, cycle time is the combined time for a series of actions that go into producing a product. Determining cycle time can help identify weak areas in the manufacturing process. To determine cycle time for the production of the compliant wind, a time study was performed. The time study involved breaking down the manufacturing process to tasks required to be performed by an operator or the machine, and observing those tasks for 10 complete cycles. The blank time study sheet can be found in Appendix A.

A stopwatch was used to time each task and the time study included observing each one of the 4 manufacturing stations for 10 consecutive cycles (40 total cycles). The focus was to include the steps that added value to production. Table 5 illustrates the average time for each step and the total average cycle time for 10 cycles. The full time study can be found for each station can be found in Appendix B.

Table 5 - Product Cycle Time

Step #	Work Element	Average Time (seconds)
1	Spool cover is lifted	3.5
2	Wire is fed to a probe	39.5
3	Machine is started and wire is held	4
4	Wind is performed by machine	179.5
5	Probe is unhooked	3.4
6	Bungee is connected to mandrel	4.7
7	Pull wire is triggered	1.4
8	Bungee ends are tied	20.5
	Total	**236**

*The amount of time that it takes to complete step 8 is not counted towards cycle time since it overlaps with the start of step 1.

As it can be seen from the above table, the average cycle time is 236 seconds (3 minutes 56 seconds). This number indicates that on average, a good unit is produced every 236 seconds. The most time consuming step is when the machine performs the wind. This step takes nearly 3 minutes. During this time, the operators are putting the finishing touches on the previous wind but most of the three minutes is spent waiting on the machine to finish its task. To better show the waiting time in one cycle time, the chart below illustrates the sequence of work elements and duration of each element.

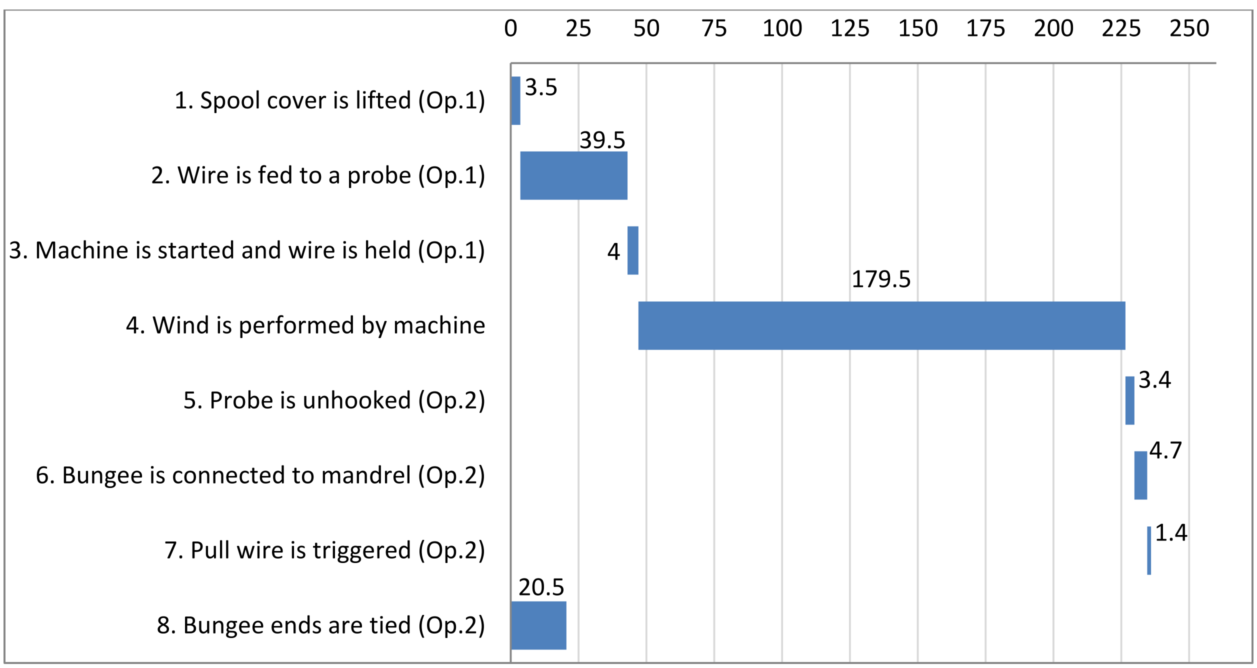

Figure 11 – Operator Work Element Sequence

The above work element sequence indicates that each operator has to wait a significant amount of time in order to perform a task, since only two tasks overlap. In other words, while the wind is being performed by the machine, operators add value to the production for only 20.5 seconds. The remaining 159 seconds is spent waiting on the machine.

Based on the current cycle time and our assumptions/parameters, the average daily production number/units produced for all four stations is (34 hr × 3600 s) ÷ 236 s = 518

3.6.2 Takt Time

Based on the average cycle time, the total number of compliant winds produced per day is 518. This is well lower than the customer demand of 600. To better understand how this number measures up to what production should be, based on our 600 unit production demand from the customer and the 34 hour planned uptime (4 stations), takt time is calculated. Takt time is calculated by simply dividing the available work time by the number of units demanded by the customer. To simplify the calculation, downtime and other work stoppages have been excluded from available work time. Therefore, we have:

$$Takt\ Time = \frac{Available\ work\ time}{Customer\ demand} \qquad (3.1)$$

$$Takt\ Time = \frac{34\ hr\ \times\ 3600\ \mathrm{s}}{600\ units}$$

$$Takt\ Time = 204\ seconds$$

Takt time for the current production of the compliant wind indicates that in order to meet the customer demand and synchronize production, a good unit must be produced every 204 seconds. This is 32 seconds lower than the current cycle time (236 seconds) and it suggests that the production is underperforming. In order to meet customer demand and reduce waste cycle time and takt time have to be synchronized.

3.6.3 Downtime

Downtime is often associated with equipment breakdowns or set-up and adjustment delays. The downtime associated with equipment breakdowns directly contributes to production. The manufacturing of the compliant wind is handled by four identical stations with each one using the same machine. The equipment in each machine is outdated and requires routine maintenance. This results in each station having to shut down for an extended period of time.

The largest downtime related to set-up and adjustments in the current production is changing the wire spool. This task has to be performed three times a day on average, per station and it takes up to four minutes. This adds up to 12 minutes per station and 48 minutes total for all stations. Keeping in mind that current cycle time is 236 seconds, in the total time spent changing wire spools, nearly 12 compliant winds could be produced.

3.6.3 Availability

The number of equipment breakdowns and any delay associated with downtime in production affect the availability of the production line. Without high availability, products cannot be manufactured at the needed rate. The existing process has high availability, indicating that production is stable. Table 6 shows the downtime and the average production availability per day.

Table 6 - Production Availability Rate

Station	Scheduled Downtime	Unscheduled Downtime	Set-up Time	Total Available Time	Production Availability
Station #1	3.3	16.3	12	510	93.8%
Station #2	16.5	10.5	12	510	92.4%
Station #3	26.4	12	12	510	90.1%
Station #4	0	13.5	12	510	95%

*All times are in minutes

Schedule Downtime: refers to planned maintenance time

Unscheduled Downtime: refers to any downtime that occurred due to equipment failure

Set-up Time: this number is associated with changing the spool

Total Available Time: one 10-hour shift minus a one hour lunch and two, fifteen minute breaks (8.5 hours = 510 minutes)

3.6.5 Overall Equipment Efficiency

To measure the current production effectiveness and pinpoint its primary weakness, the overall equipment effectiveness (OEE) is calculated. OEE is based on three main factors; equipment availability, quality yield, and cycle time performance. To calculate OEE, the assumptions and parameters mentioned in section 3.6 are used. Similar to previous measures, one month of data for each workstation was gathered and analyzed. Table 7 shows the OEE for each workstation. Entire data is listed under Appendix C.

Table 7 - Current Overall Equipment Efficiency

Station	Equipment Availability	Quality Yield	Cycle-time Performance	OEE
Station #1	93.8%	100%	79.9%	74.8%
Station #2	92.4%	99.9%	88.8%	82%
Station #3	90.1%	99.8%	87.6%	79.1%
Station #4	95%	100%	80.7%	77%

Equipment Availability: total production uptime divided by total production planned uptime

Quality Yield: total salable units divided by total units produced

Cycle-time performance: total produced units divided by the volume that should have been produced based on cycle time

Overall Equipment Efficiency (OEE): measures the equipment's performance and production results and is a product of equipment availability, quality yield, and cycle-time performance.

The OEE suggests that equipment is available for production above 90% of the time and the quality of products is near perfect. However, cycle time performance is the weakness in this production. Even though station #2 and #3 are performing at a relatively acceptable cycle time performance, station #1 and #4 are not performing as desired. The highest OEE is at 82%, which results in low equipment effectiveness and in turn low production numbers. With the production goal being 600 units per day, the OEE has to be at rates above 95%.

3.7 Summary

Based on analyses of the current manufacturing process the following observations were made:

- The overall equipment effectiveness, which is calculated based on availability, quality, and cycle time performance, is much lower than desired. This is mainly due to cycle time performance.

- The current average cycle time is 236 seconds. In order to meet daily production goal of 600 units per day, the cycle time has to be synchronized with takt time, which is 204 seconds.
- A large portion of floor space is dedicated to the manufacturing of the compliant wind. There are 4 assembly lines, each one consuming a 37 feet by 4 feet area. This means 592 square feet of floor space is consumed for the production.
- Even though the involvement of the operator with equipment has not resulted in any serious injuries, the current process has multiple ergonomic issues. These issues are mainly related to handling of the spool wire.

Chapter 4: Development of New Machine and Process

4.1 Design Objectives

The main focus in the development of the new manufacturing process and machine design is to increase the production of the compliant wind. To accomplish this goal, throughout the entire design process Lean Manufacturing concepts were used. These concepts include creating stability in the manufacturing process, increasing availability of the equipment, reducing waste, producing based on quantity needed (pull production), and designing a manufacturing system and process that is reconfigurable, maintainable and provides scientifically acceptable ergonomics.

Assessment of the current process indicates that the largest inefficiency in production is cycle time performance. In other words, it takes too much time to produce one good unit (compliant wind). Furthermore, when the entire manufacturing process was analyzed at each step of the way, the time data suggested that the primary contributor to lengthy cycle time was performing of the wind. Table 8 shows the work elements/steps and the percentage of the cycle time each step consumes.

Table 8 - Work Element Times and Percentages

Work Element	Average Time (seconds)	Percentage of Cycle Time Consumed
Spool cover is lifted	3.5	1.5%
Wire is fed to a probe	39.5	16.7%
Machine is started and wire is held	4	1.7%
Wind is performed by machine	**179.5**	**76%**
Probe is unhooked	3.4	1.4%
Bungee is connected to mandrel	4.7	2.1%
Pull wire is triggered	1.4	0.6%
Total Cycle Time	236	100%

As it can be seen from the above table, performing the wind takes 76% of the total cycle time. In addition to the time it takes the machine to perform the wind, a few more steps are needed in order to create the actual compliant wind i.e. steps needed to pull the bungee through the wind. As discussed in Chapter 3, the current process involves winding the conductor wire around a mandrel cable. Once the wind is performed, the bungee cord is pulled through the wind. This requires operator involvement and creates interruption in the manufacturing process flow.

Therefore, the primary objective of the new process and machine design is to reduce the cycle time and eliminate unnecessary work elements that result in interruption in the process flow. The new design also attempts to use modern equipment such as servomotors to alleviate maintenance concerns. Additionally, the new design focuses on maximizing floor space and providing better ergonomics.

4.2 Design Overview

In order to reduce the cycle time the new design concentrates on improving the functions needed to perform the wind. Linear motion and winding mechanism are the primary functions of the current machine. Therefore, the new manufacturing process consists of two main movements; a horizontal movement from one side to another to replace the track and trolley, and a rotary movement of two winding mechanisms to pull wire from spools and wind it on the bungee. Figure 12 shows these movements.

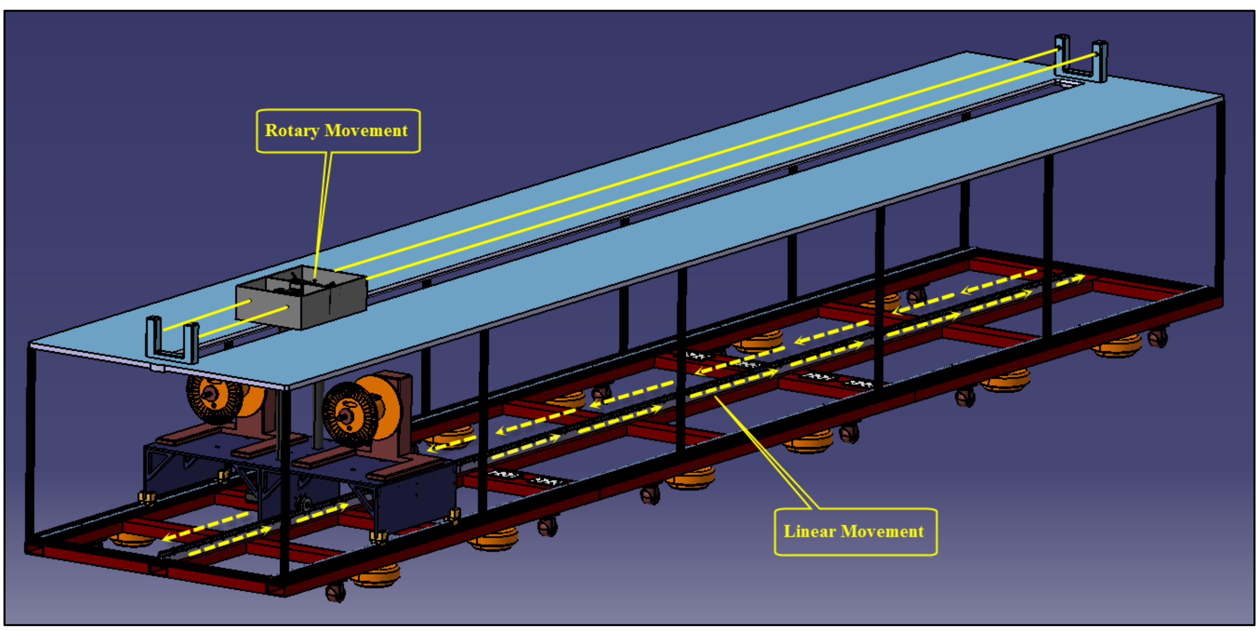

Figure 12 - Machine Movements

The assembly moves horizontally from left to right and vice versa on a rack and pinion also known as a roller pinion system (RPS). The RPS technology is commonly used in linear motion systems to convert rotary motion into linear motion. In this design, the rotary motion of a servomotor is converted to linear motion, which the assembly uses to move from one side to another. The RPS moves the assembly back and forth with zero backlashes, creating a smoother linear transition. The speed of this transition is controlled via a servomotor which is an advantage for reducing cycle time. Figure 13 illustrates the RPS system (Conway, 2006).

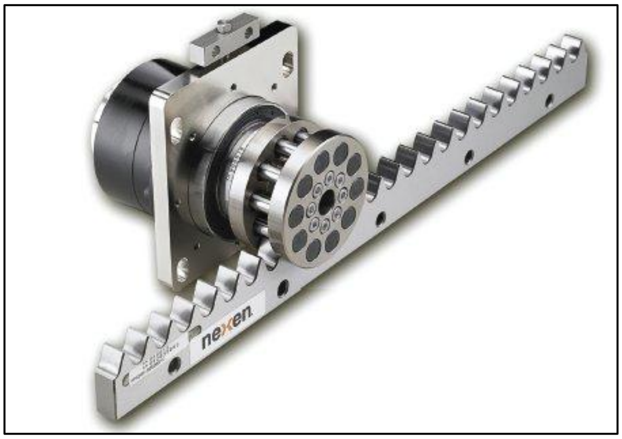

Figure 13 - Roller Pinion System

Propelled by a servomotor, the RPS moves the assembly which is consisted of a "carriage" and a "wind box". The carriage serves as a structure to move the winding mechanism from one end to another and also carries the wire spools. The speed at which the assembly moves back and forth can be adjusted by programming the servomotor. Figure 14 shows the carriage, servomotor, RPS, and the wire spools.

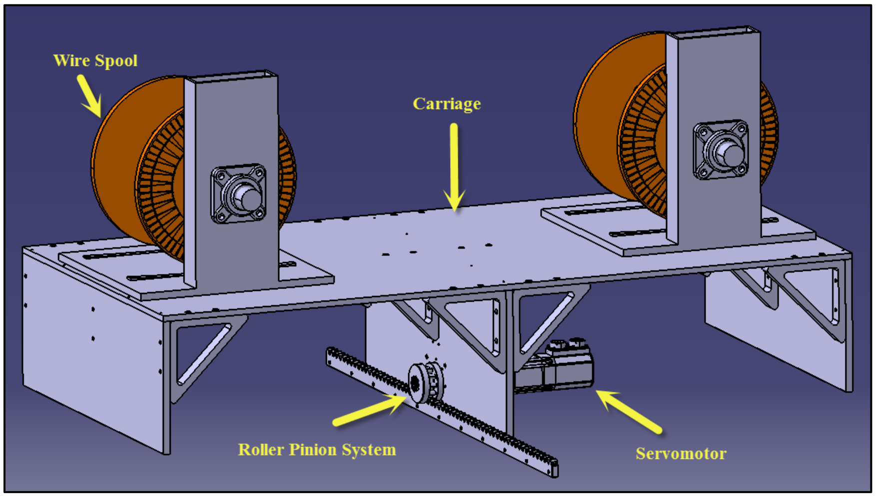

Figure 14 - Carriage, Servomotor, RPS, and Wire Spools

The wind box on the other hand, is where the winding mechanisms along with a second servomotor reside. This “box” is connected to the carriage via two shafts. Figure 15 shows the wind box.

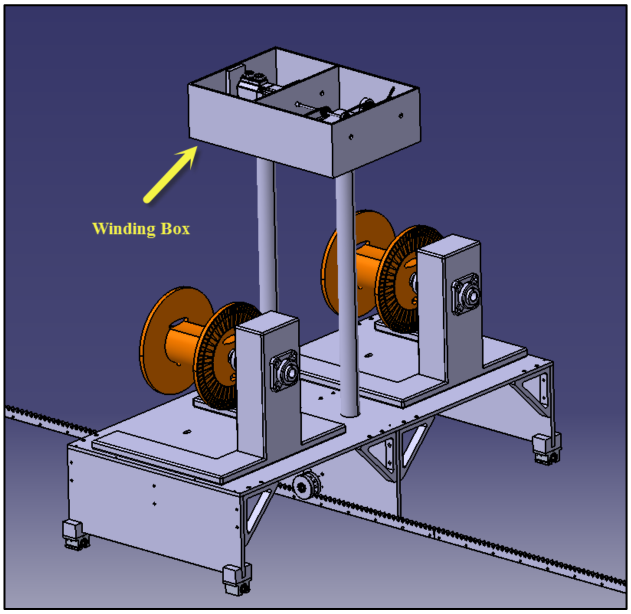

Figure 15 - Wind Box

To gain control over the wind’s diameter and pitch as well as to avoid interruption in the winding process, the new design uses the two servomotors. One motor performs the task of moving the carriage and the wind box from one end to the other using the RPS, while the second motor performs the wind in the wind box. Unlike the current process in which wire is wound around a steel mandrel cable for the bungee to be pulled through the wind, this design winds the wire directly on the bungee as it moves from one side to another.

To alleviate the vibration issues the new design eliminates the need for a wind “arm”. Instead the wind is performed using a tapered, grooved hollow shaft, powered by the servomotor to pull up wire from the spool. As wire is pulled up, the shaft keeps spinning and with the help of a guide wheel pressed on the shaft the wire takes the shape of the shaft. As the assembly moves from one end to another, the wind is passed on to the bungee. Unlike the current design, the unwrapping of the wire from spool and the winding of the wire around the bungee do not take place in the same section. Instead, the wire is unwrapped and pulled up to the wind box where the wind is performed. The separation of these two motions helps eliminate vibration and create a flow in the manufacturing process.

To help maximize the current floor space and create a less cluttered work environment, the new design uses two spools and winding mechanism per machine. This means that everytime the machine moves from one end to another, a new wind is produced. This design not only occupies less floor space, but it also helps maximize the output of the machine per cycle.

In order to eliminate ergonomic and safety issues, the involvement of each operator in the process was analyzed. The main ergonomic and safety issue is when the operator has to lift a heavy cover, which is located on the top of the assembly table, to feed the wire to the winding mechanism and also when the spool needs to be replaced. The new design takes in account the acceptable ergonomic heights and to alleviate these issues, the locations of the spools have been changed so the operators no longer have to lift the spools past their shoulder height. Instead, the spools can be replaced by being picked up off the ground and slid into a wire dereeler. Since the dereeler does not have a heavy cover, the operators do not have to lift a door in addition to lifting the wire spool. Figure 16 illustrates the steps that operator takes in the new process to replaces the spool.

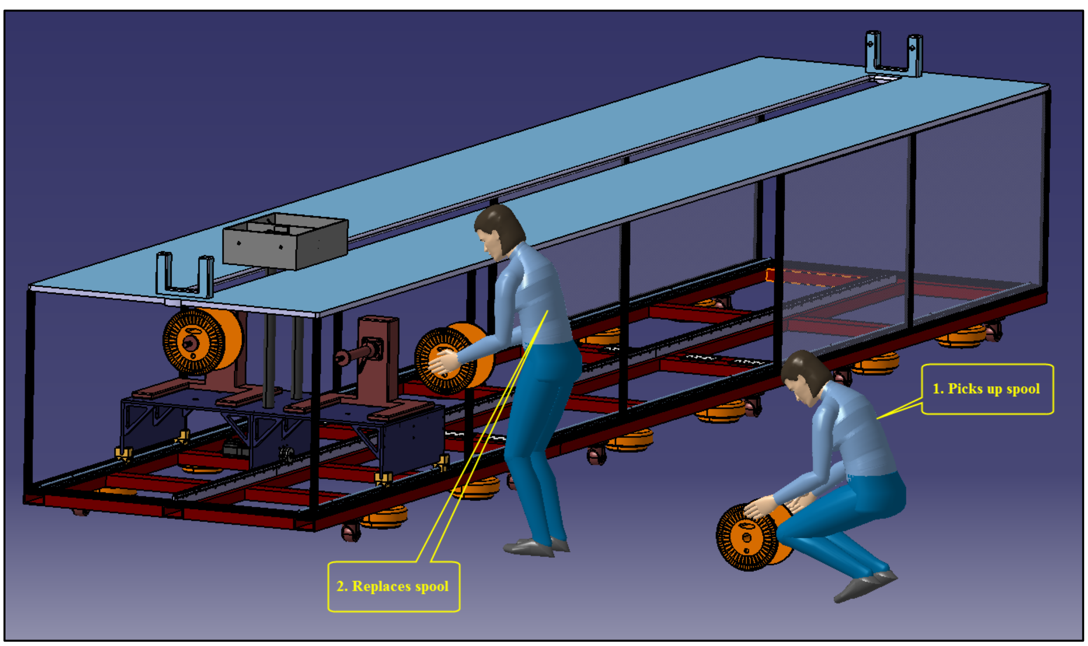

Figure 16 - Replacing wire spool

4.3 Machine Components and Assemblies

The new machine and assembly is consisted of three main subassemblies. Each subassembly and its function(s) are listed below in Table 9.

Table 9 – Machine Subassemblies and Functions

Subassembly	Function(s)
Linear Motion	- Moves wind box and wire spools to move back and forth while the wind is being performed
Wind Box	- Wraps conductor wire around bungee cord to produce the compliant wind
Base and Frame	- Provide support for the machine base - Allow linear motion components to be mounted - Enclose the machine
Control Box	- Allows operator to adjust speed of RPS as well as speed of winding mechanisms

The need for each subassembly was realized based on the design objectives. Since the primary goal of the new design was to increase production, reducing cycle time became a crucial factor. To reduce cycle time, a more efficient linear system was researched and selected. In order to standardize the work and eliminate as much human interaction with the machine as possible, the new design uses a carriage and wind box to perform the wind directly on the bungee.

A control box allows the servomotors to be programmed and move at desired speed. This gives the system the dynamic ability to adjust the movement of the machine which in turn impacts the quality of the compliant wind.

The base of the machine is designed using steel tubes and the frame is made out of 80/20. These components not only provide a rigid and safe foundation but also provide flexibility and accessibility. Each component is purchased off the shelf, eliminating the need for fabrication. This helps standardize the components and makes it convenient to order and replace parts.

The following sections explain in detail the purpose and functions of each subassembly.

4.3.1 Linear Motion

When analyzing the current complaint wind manufacturing process the need for a more efficient linear motion system became evident. This was largely due to the fact that the most time consuming task of the manufacturing process is performing the wind. The current linear motion involves a track and trolley system pulled by a motor via a cable. Even though the wind is being produced with no major issues, the speed at which the track and trolley move is slower than desired. Therefore, extensive research was done to find a more efficient linear motion system in the market. Several linear motion systems such as a belt driven system and a chain driven systems were considered. Due to the length of the product (18 feet) most linear motions systems would not be able to provide the efficiency and flexibility needed to handle the production. However, upon more research the RPS system was found. Similar to a cam and follower system the RPS is consisted of a pinion and a toothed rack. The roller bearings on the pinion are designed to always engage the rack with two contacts points, creating a backlash-free movement in both directions.

To take advantage of the roller pinion system, the current design uses the RPS to move the main assembly. The main assembly is consisted of a carriage, wire dereelers, spools, and a wind box. The RPS is powered by a servomotor and is connected to the carriage via a frame called the preloader. Figure 17 shows the carriage, RPS (pinion and toothed rack), servomotor, and preloader.

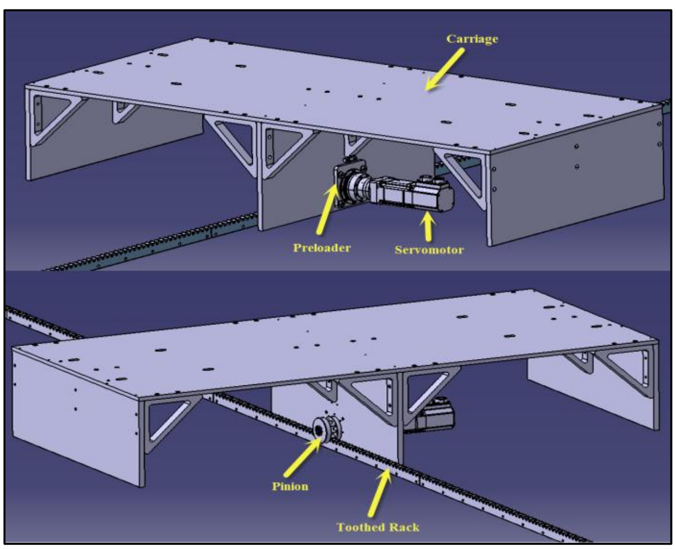

Figure 17 - Linear Motion and Carriage

The carriage is supported on each end by linear profile guides. These profiles help take the load off the RPS as well as allow the carriage to move in a straight line efficiently. The profile guide is consisted of a ball bearing and a linear rail. Figure 18 shows this component.

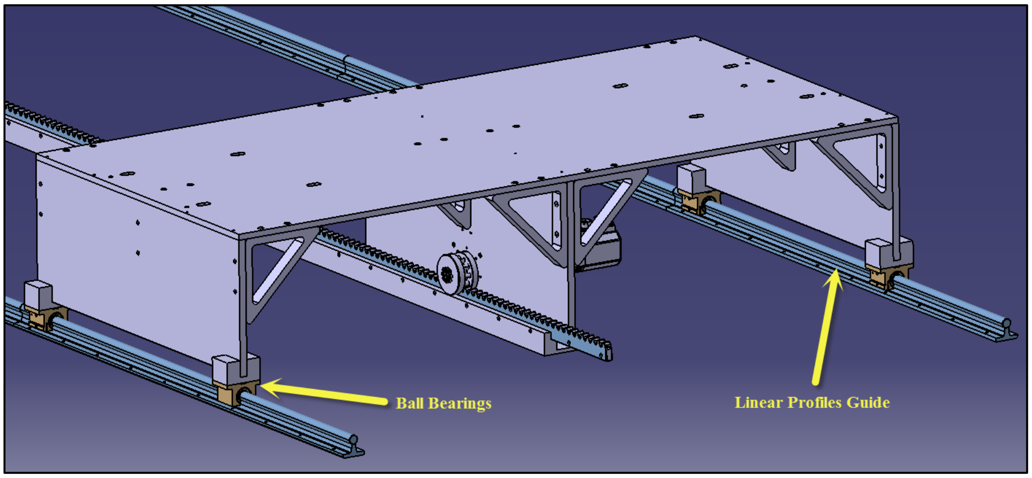

Figure 18 - Linear Profile Guides and Ball Bearings

The RPS can travel up to 36 feet per second. This range of speed allows the assembly to move much faster than the current one as long as the linear speed is synchronized with the rotation speed of the winding mechanism.

Table 10 lists the components of the linear motion assembly as well as each components function.

Table 10 - Linear Motion Assembly Components and Functions

Component	Function(s)
RPS (pinion and rack)	- Moves the assembly back and forth on a track
Servomotor	- Propels the RPS to move linearly
Carriage	- Houses wire spools - Moves the winding box
Wire Dereeler/Tensioner	- Controls the tension of wire spool and allows the spool to spin freely
Linear Profile Guides	- Provide stability for the carriage - Help the assembly move side to side - Take vertical loading off the RPS

4.3.2 Wind Box

Designing a winding mechanism that would eliminate the current issues such as controlling the pitch and diameter of the wind and reducing the time it takes to perform the wind presented many challenges. In order to overcome these challenges, the main goal of the new design was to perform the wind directly on the bungee. The ability to perform the wind on the bungee cord would eliminate the extra steps needed to pull the bungee through the wind.

To accomplish the goal of winding wire directly on the bungee the winding mechanisms are located in a "wind box" that is connected to the linear motion assembly via two stepped shafts. As the assembly moves from one end to another, the wind would be performed on the previously stretched bungee. The wind box houses two winding mechanisms powered by a servomotor. The servomotor's rotational power is translated to a shaft. The rotational movement is then translated to each winding mechanism via a one way bearing and a belt. The winding mechanisms consist of a tapered shaft and a guide wheel. As the assembly moves from one end to another, the wire is pulled up by the spinning mechanism and with the help of the guide wheel, which is pressed against the shaft to create enough friction to pull wire, the wire is wrapped around the shaft passed on to the bungee. Figure 19 show the components of the wind box.

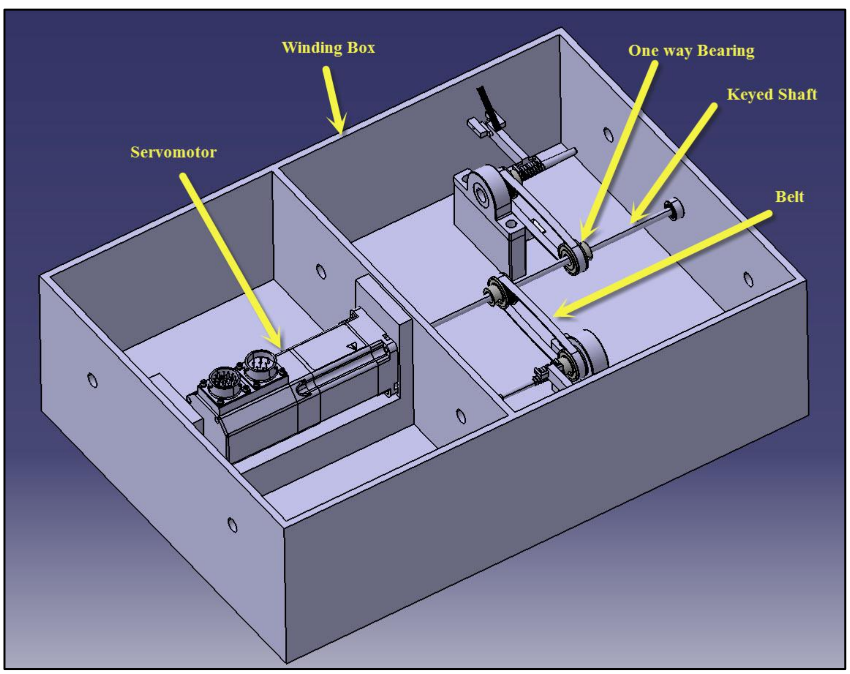

Figure 19 - Wind Box and Servomotor

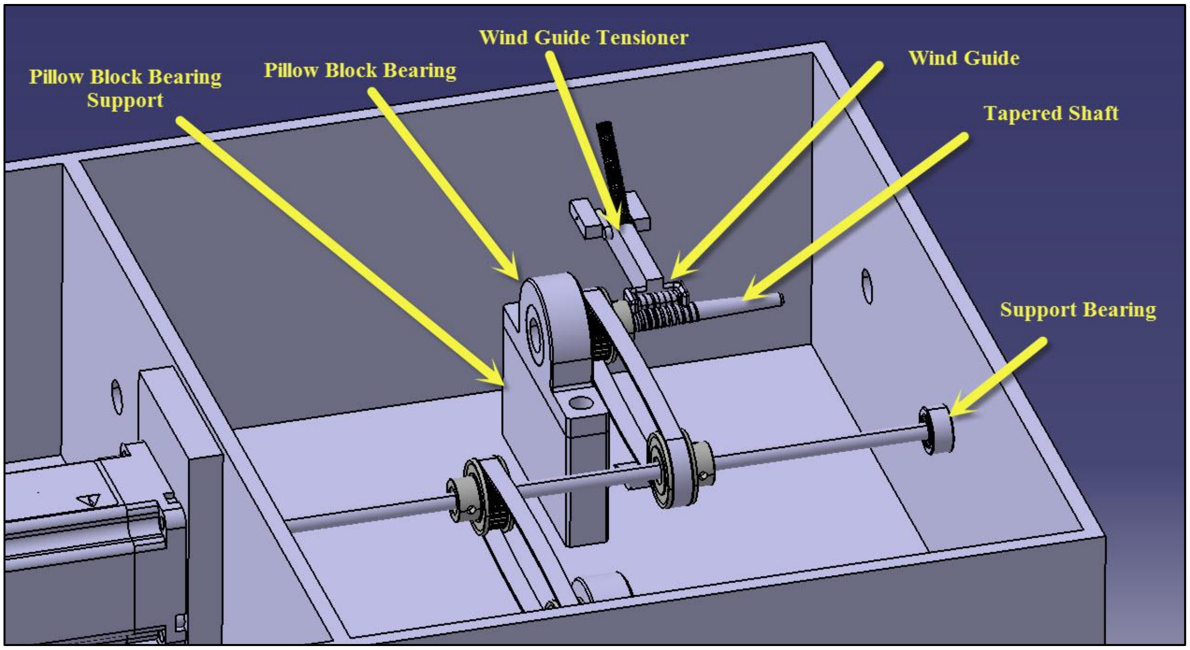

Figure 20 - Wind Box Components

The components and their functions are listed below in Table 11.

Table 11 - Wind Box Components and Functions

Component		Function(s)
Box	-	Houses winding mechanisms as well as other components needed to perform the wind
Servomotor	-	Powers winding mechanisms
Keyed Shaft	-	Serves as a tool to output the motor's power
One Way Bearing	-	Placed on the keyed shaft to allow rotation in one direction only
Belt	-	Translates rotation from keyed shaft to winding mechanism bearing
Pillow Block Bearing	-	Provides elevation for the tapered shaft and allows the bearing to spin freely
Pillow Block Bearing Support	-	Structure to support the block bearing
Support Bearing	-	Placed at the end of the keyed shaft to provide support
Tapered Shaft	-	Serves as the winding mechanism to pull up wire and wrap it around itself
Wire Guide & Tensioner	-	Provides tension on the wire that is being pulled up so it can be guided onto the tapered shaft

4.3.3 Base and Frame

The base of the machine is consisted of steel rectangular tubing to provide support for the entire assembly. The steel tubes are welded to each other and are machined to allow linear profile guides to be mounted on top of them. The base is made out of three 8 foot sections, creating a 24 feet long machine. The flexibility of having multiple sections gives Sparton the ability to easily add or remove sections if needed. Due to the length of the machine and also to give the entire assembly more flexibility and support, the base is complimented by leveling feet and caster wheels. Figure 21 illustrates these components.

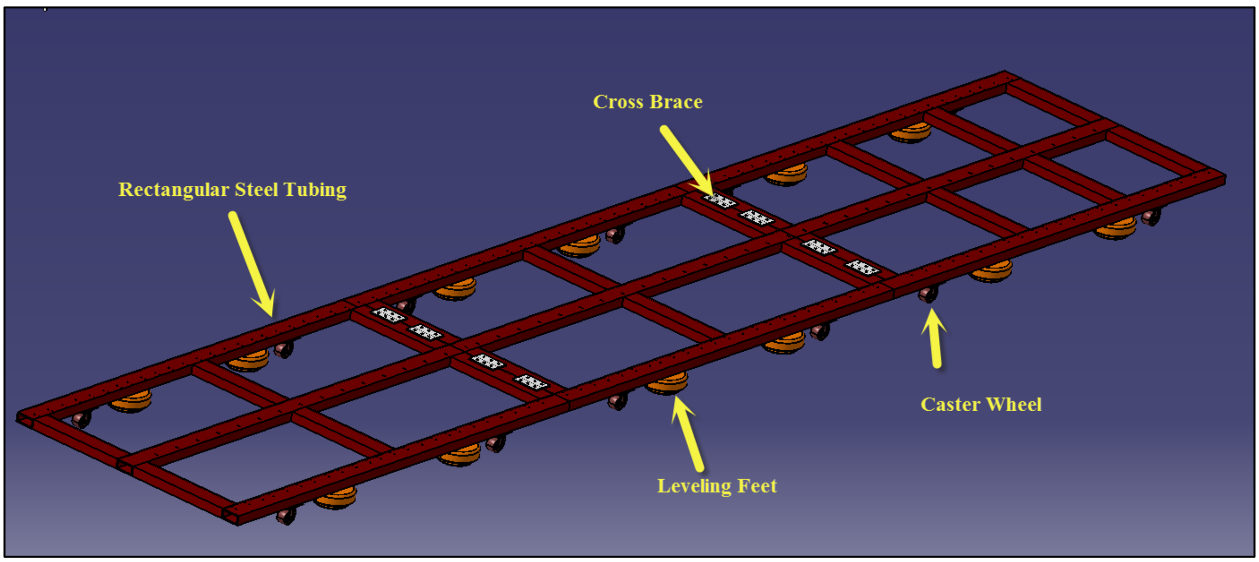

Figure 21 - Base Assembly

The main frame of the machine is created using 80/20 material. The frame is mounted on the steel tubes and supports the machine vertically. The 80/20 structure also supports the table and enables the machine to be completely enclosed using metal or plastic screens. The advantages of using 80/20 are simple construction, relatively low cost to replace, no maintenance, and reconfigurability. The frame is illustrated below in Figure 22.

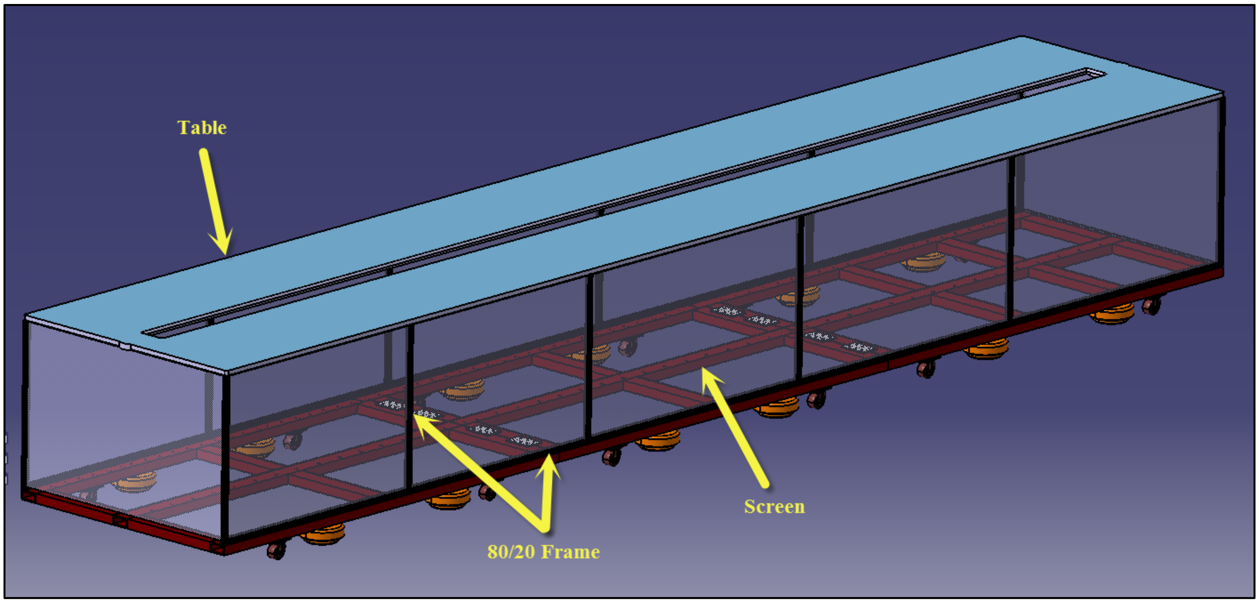

Figure 22 - Frame Assembly

The components of the base and frame assemblies are listed below in Table 12.

Table 12 - Base and Frame Components

Component	Function(s)
Rectangular Tubing	- Provide ground support for the entire machine - Allow linear motion components to be mounted on
Leveling Feet	- Help maintain a leveled machine - Adjust the height if necessary
Caster Wheels	- Provide flexibility to move machine
Cross Braces	- Connect 8 foot sections to each other
80/20	- Support the working table - Allow screens to be installed to enclose the machine
Table	- Provide an area for operators to place tools and work on

4.3.4 Control Box

The control box is a key component of the machine as it controls the speed of the linear motion system and the winding mechanisms. The control system is to have a touch screen panel which would allow engineers/operators to adjust the pitch and diameter of the compliant wind. This gives the users great flexibility and could also serve as a quality control system. Once programmed properly the control system would operate in a closed loop, allowing the machine/servomotors to stop and reset at the end of each cycle. With proper usage of sensors the operators can be notified of any issues with the manufacturing of the product at different stages.

4.4 Assembly Layout

The main layout of the new assembly is similar to the current one with a few exceptions. The new design eliminates the need for a motor at each end of the assembly. Instead, two servomotors travel back and forth with the carriage and wind box assemblies as the wind is performed. Eliminating the two motors at each end helps shorten the length of the entire assembly by four feet. The length of the table has also been shortened in the new design. The current table length is 33 feet. In the new design, this length is shortened to 24 feet. The ability to wind wire directly on the bungee enables the new design to eliminate any extra room needed for winding tasks that are no longer needed. Hence, a much shorter assembly is accomplished.

The new layout requires one operator at each end of the line. Due to the fact that the wind box has two winding mechanisms on each end of the box, operators need to perform their tasks on opposite sides of the assembly. Figure 23 shows the top view of the new assembly layout and the operators' location.

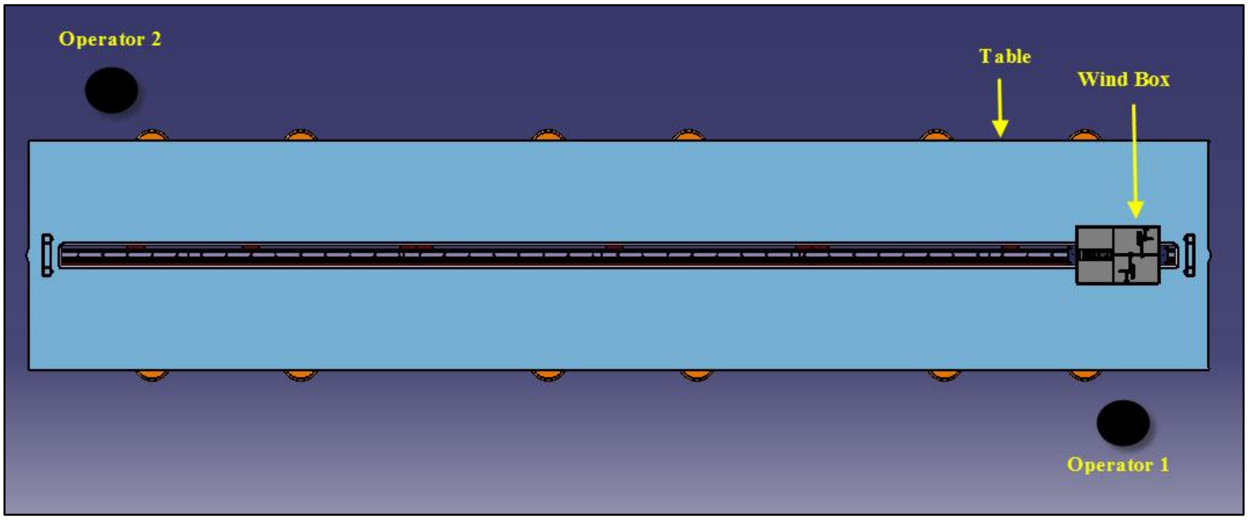

Figure 23 - Assembly Layout Top View

Figure 24 shows the assembly from the side view.

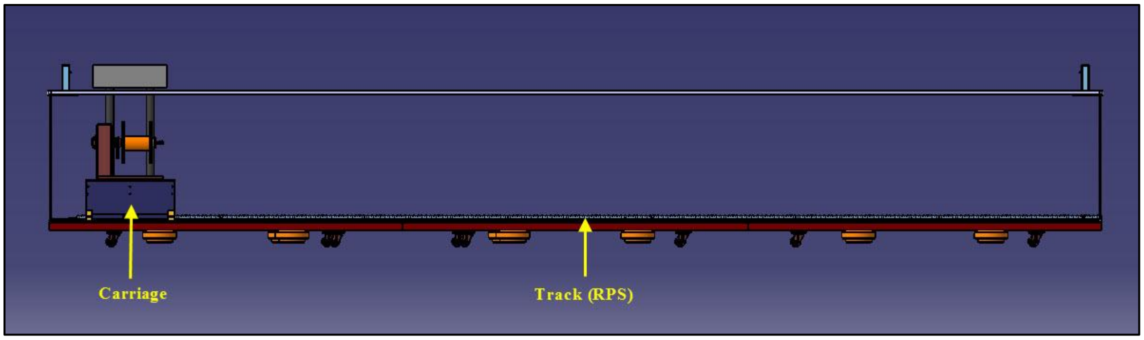

Figure 24 - Assembly Layout Side View

4.5 Overall Process Details

The manufacturing of the compliant wind using the new machine and according to the new process is as follows:

- The wind is created by wrapping the conductor wire directly on the bungee. The carriage and wind box move from one end of the assembly line to the other end to produce the wind. Powered by a servomotor, the winding mechanism in the wind box pulls up wire from the spool, located on the carriage, and wraps it around itself. As the carriage moves from one side to another, the wind moves onto the stretched bungee. Figure 25 shows the assembly movement.

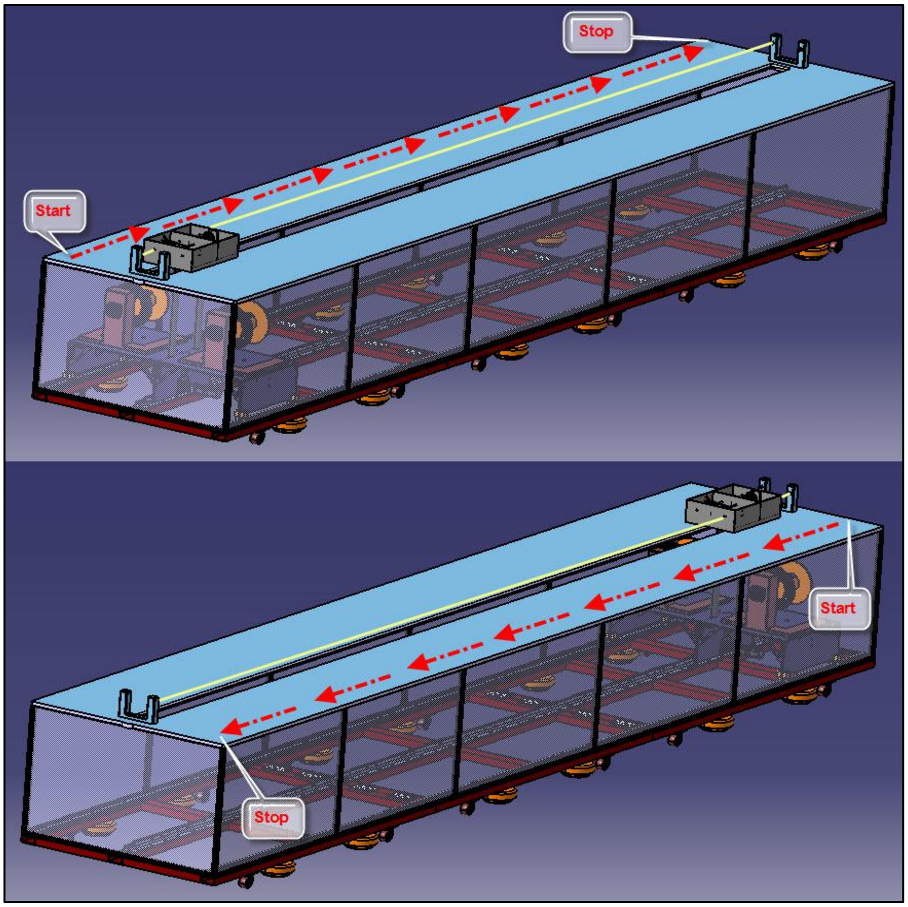

Figure 25 - Assembly/Machine Movement

- To start the process, operator attaches the bungee to the "hook" on the table and passes it through the wind box. For the first run, the bungee needs to be in tension or stretched all the way. Once the bungee is hooked and fed through, the operator starts the machine.
- The machine would perform the wind as it moves from one side to another.
- Since the machine has two winding mechanisms, at each cycle the duties of the mechanisms switch. When one of the winding mechanisms is performing the wind, the other mechanism is used as a device to stretch the bungee to the other side. When the winding process on one end is completed, the bungee on the opposite side is stretched. The mechanism that performed the wind in the last cycle now serves as the device to stretch the bungee while the other mechanism performs the wind on the bungee that was just stretched.
- When the machine reaches the other end, the operator cuts the wire and unhooks the bungee. The product is then removed.

- Similar to the current process, the operator then ties the bungee ends, and makes the manual wraps on each end to complete the product.
- This process is repeated at each cycle.

4.6 Operator Involvement

Minimizing work in progress and reducing the involvement of operators by automating manual tasks was a crucial aspect of the new design. While the number of operators per machine has not changed in the new process, the number of work elements has reduced from eight to five. This helps minimize waiting time as well as increase the efficiency of each operator. Table 13 lists the new work elements.

Table 13 - New Process Work Elements

Step #	Work Element
1	Bungee is connected to table hooks
2	Wire is fed to winding mechanism
3	Wind is performed by machine
4	Bungee is unhooked
5	Bungee ends are tied

Figure 26 illustrates the sequence of work elements and shows the duration of each task.

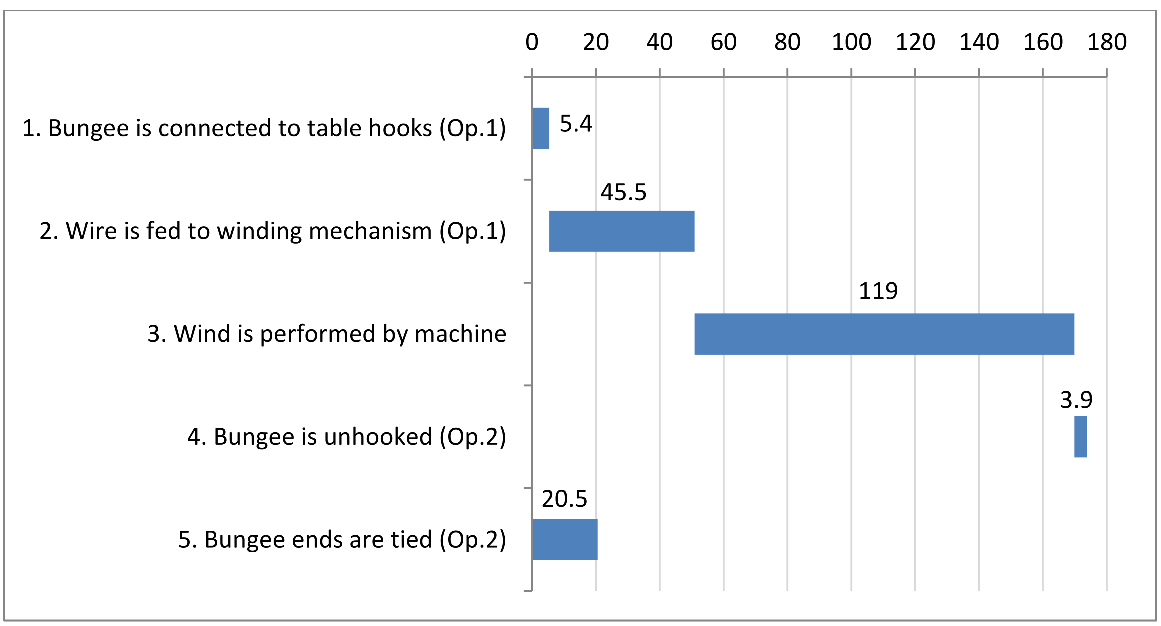

Figure 26 – Operator New Work Element Sequence

As the chart indicates, the amount waiting time has decreased from 159 seconds to 99 seconds. This is due to reducing the number of work elements as well as reducing the time the machine takes to perform the wind. Also due to the fact that the machine carries two spools and while performing the wind on one bungee cord the next wind is being set up, the amount of time that is required to set up the next wind is reduced. On successive winds, the operators switch duties and this helps establish standard work and balance the manufacturing process.

4.7 Summary

In order to accomplish the primary objective of increasing production of the compliant wind, the new design focused on reducing cycle time and work in progress as well as minimizing any interruptions in the manufacturing process by automating manual tasks. To reduce cycle time, an efficient linear motion system was designed. This system was used in conjunction with a new winding mechanism to perform the wind directly on the bungee cord which in theory would decrease work in progress and eliminate several steps in order to produce the compliant wind.

The new design also focused on creating an accessible machine that can easily be reconfigured as well as maintained. Reconfigurability of the machine was achieved by using standard and easy to assemble components such as rectangular tubing and 80/20 framing.

Chapter 5: Summary of Results

Due to lack of time and resources, the entire compliant wind machine could not be fabricated prior to the publication of this thesis. Therefore, the results in this chapter are based on time studies and theoretical numbers. In order to compare the new machine and process to the current one and also to demonstrate how Lean Manufacturing concepts can help create an efficient production system, the results are presented by quantitative and qualitative measures.

5.1 Quantitative Results

5.1.1 Cycle Time

As discussed in the previous chapter, the primary objective of the new design is to increase production of the compliant wind. A key component in production numbers is cycle time, which is the amount of time that is required to make one good product/unit. In order to understand the step-by-step process and also to find out the time it takes to complete each step, a time study was conducted. The results were presented in Chapter 3 and can also be found in Appendix B.

In comparison to the current process, the new process eliminates several work elements that are required to produce one compliant wind. Additionally, the new design takes advantage of an efficient linear motion system (RPS) to reduce the cycle time. Table 14 lists the current and new work elements.

Table 14 – Current and New Process Work Elements

Step #	Current Work Elements	New Work Elements
1	Spool cover is lifted	Bungee is connected to table hooks
2	Wire is fed to a probe	Wire is fed to winding mechanism
3	Machine is started and wire is held	Wind is performed by machine
4	Wind is performed by machine	Bungee is unhooked
5	Probe is unhooked	Bungee ends are tied
6	Bungee is connected to mandrel	n/a
7	Pull wire is triggered	n/a
8	Bungee ends are tied	n/a

The number of work elements is reduced from seven to four. The three main elements that have been removed are: lifting the spool cover, connecting the bungee to mandrel and pulling triggering the pull wire. By eliminating those steps, the involvement of operator with the machine has been minimized to what is absolutely necessary. This helps create a system that is automated and requires less human involvement. As human involvement is reduced the number of errors can be reduced.

Eliminating work elements also contributes to reducing the cycle time. To determine the time associated with performing the work elements of the new process, the time for each new work element is estimated based on a current similar task. A factor of 15% personal fatigue and delay (PF&D) is added to that estimation for tasks performed by an operator. 15% is the common standard factor for PF&D for implementing new manufacturing processes (Schokry, 2010). Since the new machine was not completely fabricated, the time associated with the machine performing the wind is calculated as follows:

The current machine performs the wind in 179.5 seconds. The distance traveled by the machine is 33 feet and 3 inches (399 in). This yields a linear speed of 0.185 ft/sec.

To calculate the time it takes to perform the wind with the new machine the same speed is used.

Velocity = 0.185 ft/sec

Distance = 22 ft

$$Velocity = \frac{Distance}{Time} \qquad (5.1)$$

$$Time = \frac{Distance}{Velocity} \qquad (5.2)$$

$$Time = \frac{22}{0.185\ ft/sec}$$

$$Time = 119\ seconds$$

Table 15 shows the current similar work elements used to estimate new work element times as well as the time estimations of the new work elements.

Table 15 - Current and New Work Elements and Times

Current Similar Work Element	Current Work Element Time	New Work Element	New Work Element Time (15% PFD)
Bungee is connected to mandrel	4.7	Bungee is connected to table hooks	5.4
Wire is fed to a probe	39.5	Wire is fed to winding mechanism	45.5
Wind is performed by machine	179.5	Wind is performed by machine	119
Probe is unhooked	3.4	Bungee is unhooked	3.9

Based on the new work elements' time, the cycle time for the new process is 173.8 seconds. Compared to the current 236 second cycle time, the new cycle time is 62.2 seconds shorter, which is largely due to a significant reduction in the time required for the machine to perform the wind. This reduction is accomplished mainly by reducing the distance traveled by the assembly that performs the wind. The machine has to travel a 22 foot distance compared to the current 33 feet distance. Logically, as distance is reduced the cycle time is reduced as well if the same speed is maintained. However, the distance traveled by the assembly cannot be any lower than 22 feet because of the product's length. The graph below, Figure 27, illustrates how distance traveled affects cycle time.

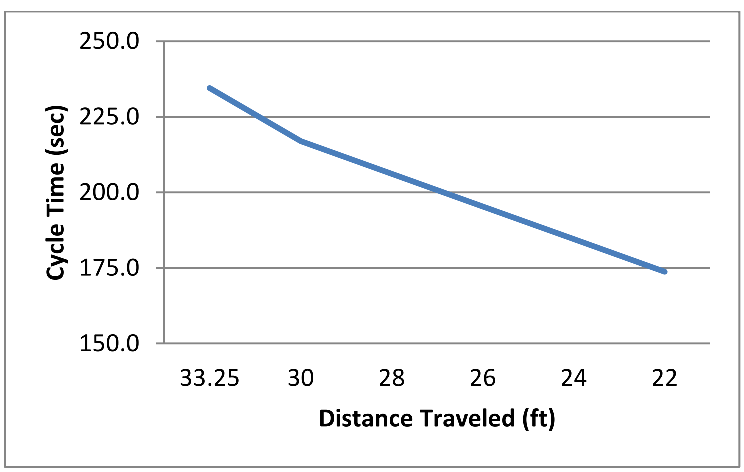

Figure 27 - Distance Traveled vs. Cycle Time

Another factor that can directly affect cycle time is the speed of the linear motion system as the assembly moves back and forth to perform the wind. The new linear motion system (RPS) has the flexibility of traveling at speeds much higher than the current system. The RPS is capable of speeds as high as 36 feet per second, but due to the fact that other machine components such as the winding mechanisms have to be in-sync with the linear movement of the entire machine, the RPS cannot operate at those high speeds. The graph below, Figure 28, illustrates the impact that linear motion system speed has on cycle time.

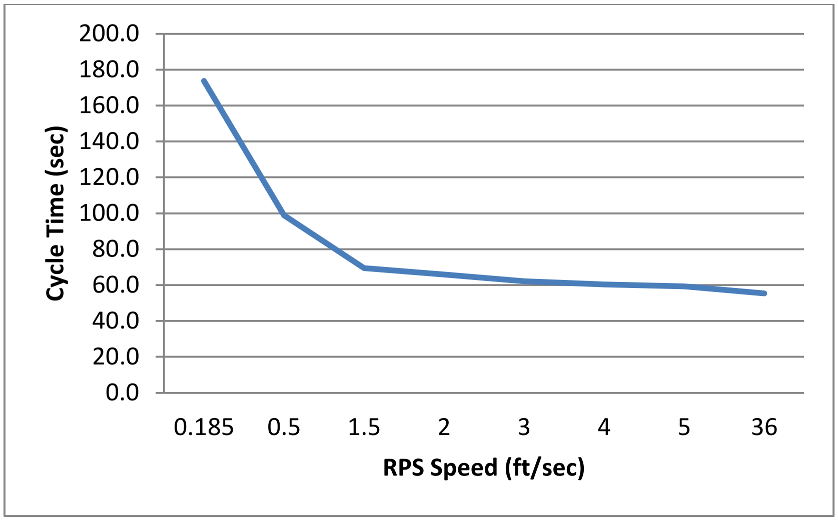

Figure 28 - Linear Motion Speed vs. Cycle Time

The graph suggests that as RPS speed increases cycle time decreases. The largest drop in cycle time is between 0.185 ft/sec to 1.5 ft/sec. For speeds higher than 1.5 ft/sec cycle time does not change drastically. This is because of the fact that speed of the RPS can only cut the time it takes to perform the wind. Other work elements consume nearly 50 seconds of cycle time. Therefore, the cycle time plateaus at that range.

5.1.2 Production Numbers

The immediate result of reduced cycle time is increased production. The graph below, Figure 29, shows the daily production of the current and new process based on the work elements and times presented in Table 15.

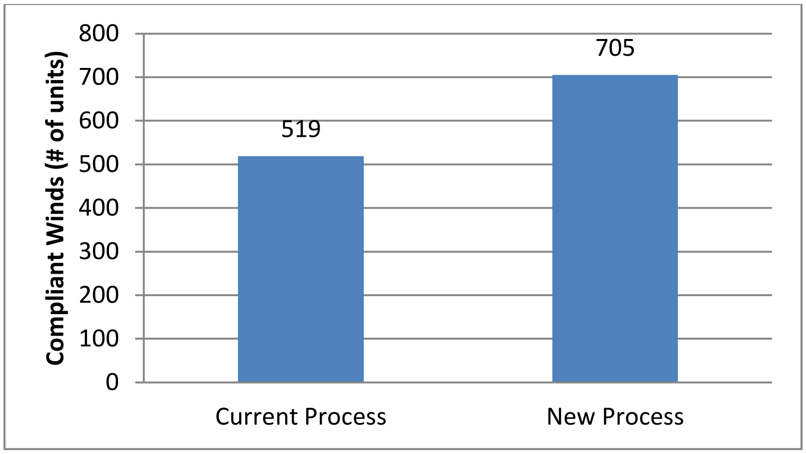

Figure 29 - Current vs. New Production Numbers

The new process increases production by 186 units. This increase is a direct result of reduced cycle time which is achieved by minimizing work elements to what is absolutely necessary and shortening the distance traveled by the assembly. The production can increase even more by increasing the speed of the linear motion system. The following graph, Figure 30, shows the number of units that can theoretically be produced based on the speed of the linear motion system.

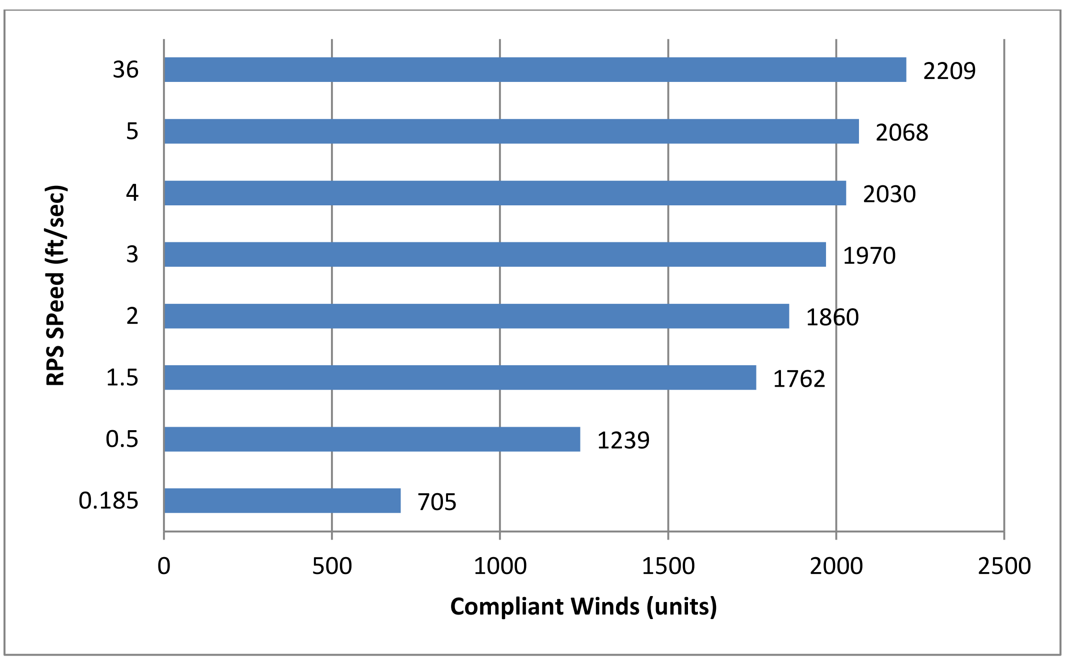

Figure 30 - Production by RPS Speed

Takt Time Production

In order to establish a pull production system that is based on customer demand, the cycle time has to be synchronized with takt time. As discussed in Chapter 3, the takt time is 204 seconds. This is based on 34 hour equipment availability (4 stations operating 8.5 hours a day) and a 600 unit daily customer demand. Since the new process cycle time is 173.8 seconds, the production system would over perform. Overproduction is considered a waste in a pull production system. Therefore, to synchronize cycle time and takt time and to create an efficient pull production system the following changes need to be made:

- Decrease the number of stations from 4 to 2. This would decrease planned uptime from 34 hours to 17 hours and takt time from 204 seconds to 102 seconds.
- Match cycle time to takt time by increasing linear motion speed from 0.185 ft/sec to 0.47 ft/sec

These changes would help the production system meet its daily goal of 600 units while freeing up floor space and eliminating four operators. With each assembly occupying a 37 feet by 4 feet area (148 sq. ft.), eliminating two assembly lines would create 296 square feet of floor space.

Furthermore, eliminating four operators would save the company a significant amount of money. Each operator works four days a week, 10 hours a day and is paid $10 an hour. The graph below, Figure 31, shows the amount of money Sparton could save by eliminating two assembly lines and four operators on daily, weekly, monthly, quarterly, and annual basis.

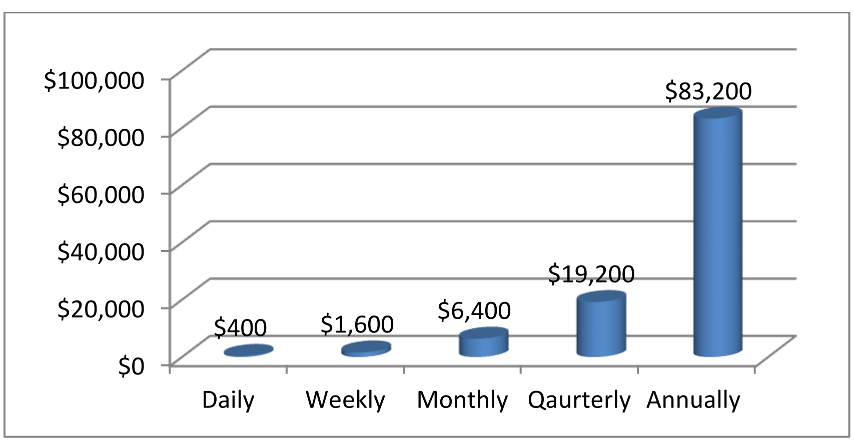

Figure 31 - Sparton Savings

The savings illustrated in Figure 33 are solely based on employee hourly wages. These savings do not include factors such as employee benefits, savings in utilities, and floor space. Though difficult to quantify, these factors all contribute to more spending which can be prevented with the new machine and process.

5.2 Qualitative Results

5.2.1 Standard Work and Flow

The new process reduces the number of work elements required to produce the compliant wind. Additionally, each work element is clearly defined to standardize the entire process. The work elements in order are:

1. Connect bungee to table hooks
2. Feed wire to winding mechanism
3. Start Machine
4. Unhook bungee

In comparison to the current process in which operators swap duties and several tasks overlap one another, the new process outlines a set of standard steps that need to be completed. Standard work not only eliminates confusion but also creates flow in the manufacturing process and helps make training new operators much simpler.

5.2.2 Reconfigurability

The base of the new machine is designed in eight feet sections that can dissemble since they are bolted together. With the help of caster wheels and leveling feet, each section of the assembly can be moved easily. Figure 32 shows the cross bolted connections.

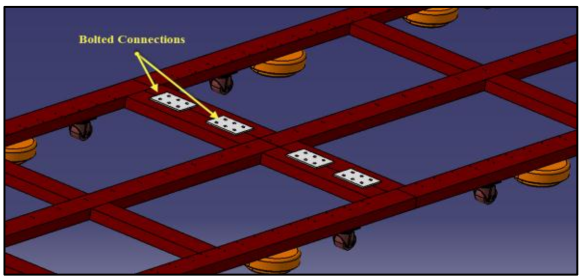

Figure 32 - Bolted Connections

The frame of the machine is designed using 80/20 T-slotted structure. This allows the height of the table to be adjusted by simply using different length 80/20. In addition to height adjustments, the 80/20 structure allows Plexiglas screen doors to be put in place in order to enclose the entire machine.

5.2.3 Ergonomics

The main ergonomic issues with the current process involve lifting the wire spool when it needs to be replaced and also lifting (opening and closing) a relatively heavy door/cover to pull wire from the spool in order to feed it to the track and trolley. These issues are alleviated with the new machine design. The spool has been moved from the top of the table to the bottom of the table. This eliminates any extension of the arms and shoulder above normal range as well having to lift a 25 pound spool beyond ergonomic range multiple times a day. Figure 33 illustrates the operator posture for changing the wire spool.

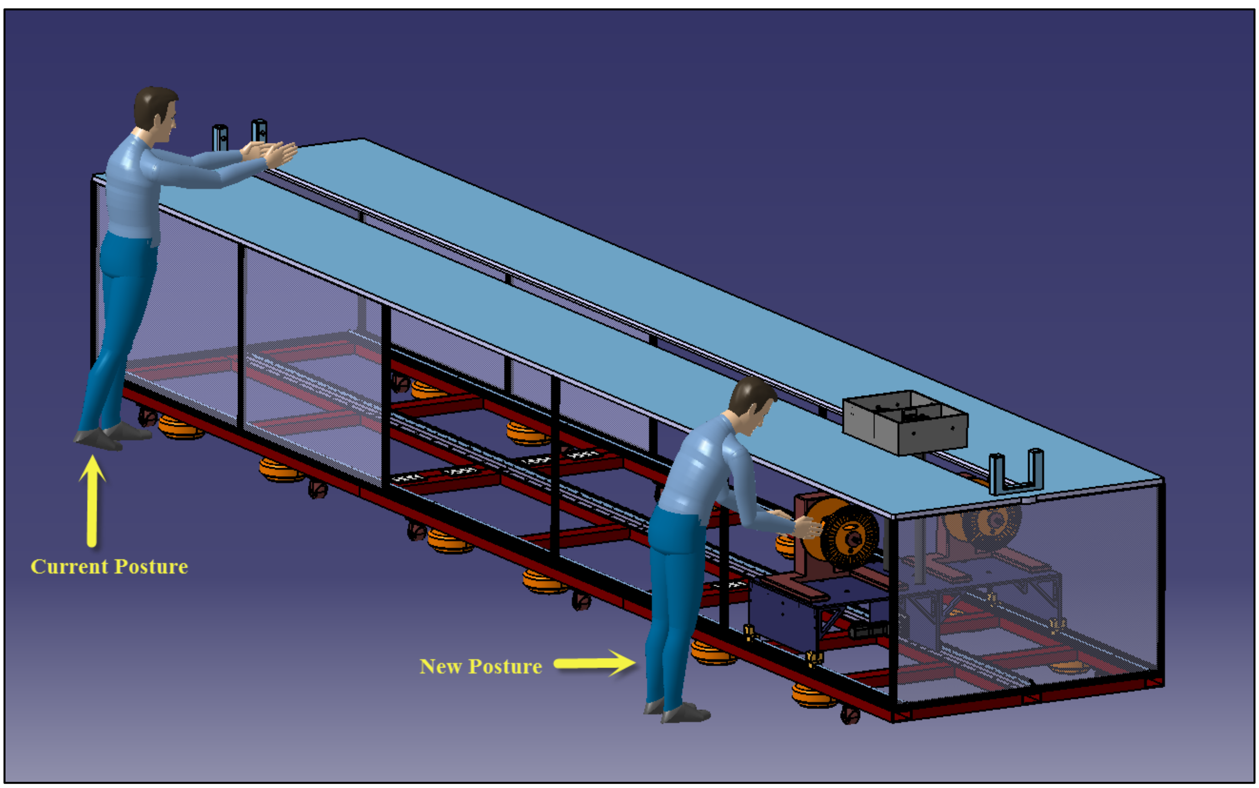

Figure 33 - Operator Posture

The new design requires the operator to slightly bend to reach the spool. The dereeler that holds the spool has the ability to slide out to further assist the operator. In comparison to the current operator posture, the new posture does not require lifting the spool and having to each over the table to replace it.

Due to the fact that the entire carriage and spool assembly are under the table and are enclosed the need for a spool cover has been eliminated. The dereeler holds the spool in place and provides tension for the wire as it is being unwrapped.

5.3 Summary

In Summary, the new machine can theoretically reduce operator waiting time and excess movement and increase the speed at which the components can function. This directly affects product cycle time which in turn impacts total production numbers. The new process standardizes the work elements and establishes flow and balance in the manufacturing process. The reconfigurability of the machine makes it easier to assemble and disassemble components and also creates accessibility for maintenance. The new machine design also minimizes ergonomic issues by relocating components such as the wire spool and winding mechanisms.

Chapter 6: Conclusions and Future Considerations

6.1 Conclusions

This thesis presented the current obstacles faced by Sparton Electronics in the manufacturing and production of the compliant wind. The obstacles included dealing with outdated equipment that were difficult to maintain, inconsistency in pitch and diameter of the compliant wind, ergonomics, high work in progress and cycle time, and most importantly not meeting production goals. To alleviate these issues, Lean Manufacturing tools and techniques were used. Lean Manufacturing was researched and studied in detail to determine its most effective tools. These concepts were then categorized in two ways; whether the concepts focused on the qualitative aspects or if they focused on quantitative aspects of manufacturing. Categorizing lean tools and concepts helped pinpoint the source of each issue.

Once the source of each issue became clear, the primary objective of the new design was to increase production. With that objective in mind, the new process and machine were developed to meet that goal. Quantitatively, the focus was to design a machine that could reduce product cycle time as well as work in progress. On the other hand, the qualitative focus was on increasing the availability of the machine, creating a more stable process, establishing flow, and standardizing work elements.

The result of the new design is a machine and process that is modern and efficient. The issues with inconsistency in product pitch and diameter are addressed by using servomotors and a controls system. With the new design the operators are given the ability to use a computer interface to adjust and control the product. The cycle time and work in progress are reduced by using an efficient linear motion system and shortening the length of the assembly. This in turn results in an increase in production numbers. The concept of just in time production and takt time are used to balance the cycle time and ensure that the customer demand is met.

The ergonomic concerns were mainly related to lifting heavy objects i.e. wire spools and spool covers. These concerns are addressed in the new design by eliminating the need to lift the spool above the table. The wire spools are positioned under the table on a carriage. The spools are held in place by a dereeler that slides out. The operator can simply slide out the spool assembly and replace the spool by picking it up only inches from the ground.

Overall, even though the machine was not completely fabricated and the new process was not tested, theoretical values based on time studies and research indicate that the new design is a far more efficient and lean approach for the manufacturing of the compliant wind.

6.2 Future Considerations

While the design aspect of this project was completed and most of the equipment were purchased, only an 8 foot section of the machine base along with the carriage were fabricated. The next steps for Sparton Electronics include fabricating and purchasing the wind box components, fabricating the base and frame components, assembling the carriage, programing the servo for the linear motion, and running the assembly on the RPS track. Once linear motion is tested, the wind box servomotor and winding mechanisms have to be synchronized with the speed of the linear motion via the controls system. The system should include sensors and provide feedback to operators at critical stages of manufacturing to avoid quality issues. After the system is fully set up extensive testing needs to be done to ensure the machine can perform as needed. The last step is to provide training for operators.

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Appendices

Appendix A: Compliant Wind Production Blank Time Study

Process to Monitor: Compliant Wind																Date: 03/05/2014, 1st shift
Station: 1																Done By: Arash Sabet-Rasekh
*All cycle times are in seconds																
Step No	**Work Element**	**Cycle 1**	**Cycle 2**	**Cycle 3**	**Cycle 4**	**Cycle 5**	**Cycle 6**	**Cycle 7**	**Cycle 8**	**Cycle 9**	**Cycle 10**	**High**	**Low**	**Range**	**Average**	**Final**
1	Lift Spool Cover															
2	Feed wire to probe															
3	Start machine, hold wire															
4	Perform wind															
5	Unhook probe															
6	Connect bungee to mandrel															
7	Trigger pull wire															
	Totals															
Notes:																

Appendix B: Compliant Wind Production Time Study for Stations 1 through 4

Process to Monitor: Compliant Wind | **Date: 03/05/2014, 1st shift**

Station: 1 | **Done By: Arash Sabet-Rasekh**

***All cycle times are in seconds**

Step No	Work Element	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7	Cycle 8	Cycle 9	Cycle 10	High	Low	Range	Average	Final
1	Lift Spool Cover	4	3	3	4	3	4	4	3	3	4	4	3	1	3.5	4
2	Feed wire to probe	42	38	31	46	40	35	33	39	46	44	46	31	15	39.4	44
3	Start machine, hold wire	3	5	5	4	5	4	3	4	3	4	5	3	2	4	4
4	Perform wind	181	179	180	180	178	179	178	179	178	180	181	178	3	179.2	180
5	Unhook probe	4	3	4	3	3	4	4	4	3	3	4	3	1	3.5	3
6	Connect bungee to mandrel	5	5	6	6	5	4	4	4	4	5	6	4	2	4.8	5
7	Trigger pull wire	1	1	1	1	2	1	2	1	2	1	2	1	1	1.3	1
	Totals	240	234	230	244	236	231	228	234	239	241	248	223	n/a	235.7	241
Notes:	1. Two additional steps are required to complete the product; tying bungee ends and wrapping bungee in a black sheet. These steps overlap with the next wind being produced. Therefore, they are not contributing to the actual cycle time and are not considered in time studies.															
	2. Changing spool takes up to 4 minutes; this is done at least 3 times a day.															

Process to Monitor: Compliant Wind Station: 2 *All cycle times are in seconds								Date: 03/05/2014, 1st shift Done By: Arash Sabet-Rasekh							
Step No	**Work Element**	**Cycle 1**	**Cycle 2**	**Cycle 3**	**Cycle 4**	**Cycle 5**	**Cycle 6**	**Cycle 7**	**Cycle 8**	**Cycle 9**	**Cycle 10**	**High**	**Low**	**Range**	**Average**	**Final**
1	Lift Spool Cover	4	3	3	4	3	4	4	3	3	4	4	3	1	3.5	4
2	Feed wire to probe	42	38	33	46	40	35	33	39	45	44	46	33	13	39.5	44
3	Start machine, hold wire	3	5	5	4	5	4	3	4	3	4	5	3	2	4	4
4	Perform wind	180	179	181	180	180	180	178	179	178	180	181	178	3	179.5	180
5	Unhook probe	4	3	4	3	3	4	4	3	3	3	4	3	1	3.4	3
6	Connect bungee to mandrel	5	4	5	6	5	4	5	4	4	5	6	4	2	4.7	5
7	Trigger pull wire	1	2	1	1	2	1	2	1	2	1	2	1	1	1.4	1
	Totals	239	234	232	244	238	232	229	233	238	241	248	225	n/a	236	241
Notes:	1. Two additional steps are required to complete the product; tying bungee ends and wrapping bungee in a black sheet. These steps overlap with the next wind being produced. Therefore, they are not contributing to the actual cycle time and are not considered in time studies.															
	2. Changing spool takes up to 4 minutes; this is done at least 3 times a day.															

Process to Monitor: Compliant Wind Station: 3 *All cycle times are in seconds												Date: 03/05/2014, 1st shift Done By: Arash Sabet-Rasekh				
Step No	**Work Element**	**Cycle 1**	**Cycle 2**	**Cycle 3**	**Cycle 4**	**Cycle 5**	**Cycle 6**	**Cycle 7**	**Cycle 8**	**Cycle 9**	**Cycle 10**	**High**	**Low**	**Range**	**Average**	**Final**
1	Lift Spool Cover	3	3	4	4	3	4	4	3	3	4	4	3	1	3.5	4
2	Feed wire to probe	42	38	31	45	40	35	32	39	46	44	45	31	14	39.2	44
3	Start machine, hold wire	3	5	5	4	5	4	3	4	3	4	5	3	2	4	4
4	Perform wind	180	179	180	180	178	180	178	179	178	180	180	179	1	179.2	180
5	Unhook probe	3	3	4	3	3	4	4	4	3	3	4	3	1	3.4	3
6	Connect bungee to mandrel	5	5	6	5	5	4	4	4	4	5	6	4	2	4.7	5
7	Trigger pull wire	2	1	1	1	2	1	2	1	2	1	2	1	1	1.4	1
	Totals	238	234	231	242	236	232	227	234	239	241	246	224	n/a	235.4	241
Notes:	1. Two additional steps are required to complete the product; tying bungee ends and wrapping bungee in a black sheet. These steps overlap with the next wind being produced. Therefore, they are not contributing to the actual cycle time and are not considered in time studies.															
	2. Changing spool takes up to 4 minutes; this is done at least 3 times a day.															

Process to Monitor: Compliant Wind Station: 4 *All cycle times are in seconds									Date: 03/05/2014, 1st shift Done By: Arash Sabet-Rasekh						
Step No	**Work Element**	**Cycle 1**	**Cycle 2**	**Cycle 3**	**Cycle 4**	**Cycle 5**	**Cycle 6**	**Cycle 7**	**Cycle 8**	**Cycle 9**	**Cycle 10**	**High**	**Low**	**Range**	**Average**	**Final**
1	Lift Spool Cover	3	3	3	4	3	4	4	3	3	3	4	3	1	3.3	3
2	Feed wire to probe	42	38	31	45	39	36	32	39	46	41	45	31	14	38.9	41
3	Start machine, hold wire	3	3	5	4	5	4	3	4	3	4	5	3	2	3.8	4
4	Perform wind	181	179	180	180	179	180	178	180	178	180	181	179	2	179.5	180
5	Unhook probe	4	3	4	3	3	4	4	3	3	3	4	3	1	3.4	3
6	Connect bungee to mandrel	5	5	6	5	5	5	4	4	4	5	6	4	2	4.8	5
7	Trigger pull wire	2	1	2	1	2	1	2	1	2	1	2	1	1	1.5	1
	Totals	240	232	231	242	236	234	227	234	239	237	247	224		235.2	237
Notes:	1. Two additional steps are required to complete the product; tying bungee ends and wrapping bungee in a black sheet. These steps overlap with the next wind being produced. Therefore, they are not contributing to the actual cycle time and are not considered in time studies.															
	2. Changing spool takes up to 4 minutes; this is done at least 3 times a day.															

Appendix C: Overall Equipment Effectiveness – Station 1

Date	Good Parts	Bad Parts	Total Production	Scheduled Downtime	Unscheduled Downtime	Availability	Performance Rate	Quality Rate	OEE
11/25/2013	96	0	96	0	0	97.6%	64.0%	100.0%	62.5%
11/26/2013	100	0	100	0	0	97.6%	66.7%	100.0%	65.1%
11/27/2013	86	0	86	0	0	97.6%	57.3%	100.0%	56.0%
12/2/2013	80	0	80	0	0	97.6%	53.3%	100.0%	52.1%
12/3/2013	102	0	102	0	0	97.6%	68.0%	100.0%	66.4%
12/4/2013	111	0	111	0	0	97.6%	74.0%	100.0%	72.3%
12/5/2013	125	0	125	0	0	97.6%	83.3%	100.0%	81.4%
12/9/2013	125	0	125	0	0	97.6%	83.3%	100.0%	81.4%
12/10/2013	71	0	71	0	10	95.7%	48.1%	100.0%	46.1%
12/11/2013	125	0	125	0	0	97.6%	83.3%	100.0%	81.4%
12/12/2013	130	0	130	0	0	97.6%	86.7%	100.0%	84.6%
12/16/2013	150	0	150	0	0	97.6%	100.0%	100.0%	97.6%
12/17/2013	144	0	144	0	10	95.7%	97.6%	100.0%	93.4%
12/18/2013	150	0	150	0	80	82.0%	115.4%	100.0%	94.6%
1/6/2014	120	0	120	0	0	97.6%	80.0%	100.0%	78.1%
1/7/2014	108	0	108	0	40	89.8%	77.1%	100.0%	69.3%
1/8/2014	100	0	100	0	0	97.6%	66.7%	100.0%	65.1%
1/13/2014	34	0	34	0	0	97.6%	22.7%	100.0%	22.1%
1/14/2014	55	0	55	0	0	97.6%	36.7%	100.0%	35.8%
1/15/2014	105	0	105	0	0	97.6%	70.0%	100.0%	68.4%
1/16/2014	150	0	150	0	0	97.6%	100.0%	100.0%	97.6%
1/20/2014	81	0	81	0	60	85.9%	60.0%	100.0%	51.5%
1/21/2014	106	0	106	0	0	97.6%	70.7%	100.0%	69.0%
1/22/2014	112	0	112	0	0	97.6%	74.7%	100.0%	72.9%
1/23/2014	95	0	95	0	0	97.6%	63.3%	100.0%	61.8%

1/27/2014	101	0	101	0	0	97.6%	67.3%	100.0%	65.7%
1/28/2014	118	0	118	0	0	97.6%	78.7%	100.0%	76.8%
1/29/2014	137	0	137	0	0	97.6%	91.3%	100.0%	89.2%
1/30/2014	150	0	150	0	0	97.6%	100.0%	100.0%	97.6%
2/3/2014	144	0	144	0	0	97.6%	96.0%	100.0%	93.7%
2/4/2014	134	0	134	0	0	97.6%	89.3%	100.0%	87.2%
2/5/2014	130	0	130	0	30	91.8%	91.2%	100.0%	83.7%
2/6/2014	137	1	138	0	0	97.6%	92.0%	99.3%	89.2%
2/10/2014	96	0	96	0	0	97.6%	64.0%	100.0%	62.5%
2/11/2014	79	0	79	0	180	62.4%	75.2%	100.0%	46.9%
2/12/2014	160	0	160	0	0	97.6%	106.7%	100.0%	104.2%
2/13/2014	158	0	158	0	0	97.6%	105.3%	100.0%	102.9%
2/14/2014	103	0	103	150	0	68.2%	91.6%	100.0%	62.5%
2/17/2014	135	0	135	0	0	97.6%	90.0%	100.0%	87.9%
2/18/2014	138	0	138	0	30	91.8%	96.8%	100.0%	88.9%
2/19/2014	146	0	146	0	0	97.6%	97.3%	100.0%	95.0%
2/20/2014	115	0	115	0	100	78.0%	92.0%	100.0%	71.8%
2/24/2014	146	0	146	0	0	97.6%	97.3%	100.0%	95.0%
2/25/2014	144	0	144	0	0	97.6%	96.0%	100.0%	93.7%
2/26/2014	76	0	76	0	210	56.5%	77.9%	100.0%	44.0%
2/27/2014	116	0	116	0	0	97.6%	77.3%	100.0%	75.5%
Totals	**115.7**	**0.0**	**115.8**	**3.3**	**16.3**	**93.8%**	**79.9**	**100.0**	**74.8**

Appendix D: Overall Equipment Effectiveness – Station 2

Date	Good Parts	Bad Parts	Total Production	Scheduled Downtime	Unscheduled Downtime	Availability	Performance Rate	Quality Rate	OEE
1/21/2014	96	0	96	0	0	97.6%	64.0%	100.0%	62.5%
1/22/2014	150	0	150	0	0	97.6%	100.0%	100.0%	97.6%
1/23/2014	93	1	94	0	30	91.8%	66.0%	98.9%	59.9%
1/27/2014	108	0	108	0	0	97.6%	72.0%	100.0%	70.3%
1/28/2014	150	0	150	0	0	97.6%	100.0%	100.0%	97.6%
1/29/2014	150	0	150	90	40	72.2%	127.7%	100.0%	92.1%
1/30/2014	137	2	139	0	40	89.8%	99.3%	98.6%	87.9%
2/3/2014	106	0	106	0	0	97.6%	70.7%	100.0%	69.0%
2/4/2014	132	0	132	0	0	97.6%	88.0%	100.0%	85.9%
2/5/2014	103	0	103	0	0	97.6%	68.7%	100.0%	67.1%
2/6/2014	122	0	122	0	0	97.6%	81.3%	100.0%	79.4%
2/10/2014	132	0	132	0	0	97.6%	88.0%	100.0%	85.9%
2/11/2014	115	0	115	0	0	97.6%	76.7%	100.0%	74.9%
2/12/2014	160	0	160	0	0	97.6%	106.7%	100.0%	104.2%
2/13/2014	160	0	160	0	0	97.6%	106.7%	100.0%	104.2%
2/24/2014	150	0	150	0	0	97.6%	100.0%	100.0%	97.6%
2/25/2014	150	0	150	0	100	78.0%	120.0%	100.0%	93.6%
2/26/2014	137	0	137	0	0	97.6%	91.3%	100.0%	89.2%
2/27/2014	144	0	144	0	0	97.6%	96.0%	100.0%	93.7%
2/28/2014	48	0	48	240	0	50.6%	53.3%	100.0%	27.0%
Totals	**127.2**	**0.2**	**127.3**	**16.5**	**10.5**	**92.4%**	**88.8**	**99.9**	**82.0**

Appendix E: Overall Equipment Effectiveness – Station 3

Date	Good Parts	Bad Parts	Total Production	Scheduled Downtime	Unscheduled Downtime	Availability	Performance Rate	Quality Rate	OEE
1/20/2014	84	0	84	0	10	95.7%	56.9%	100.0%	54.5%
1/21/2014	112	0	112	0	0	97.6%	74.7%	100.0%	72.9%
1/22/2014	95	0	95	0	0	97.6%	63.3%	100.0%	61.8%
1/23/2014	100	0	100	0	0	97.6%	66.7%	100.0%	65.1%
1/27/2014	120	0	120	0	0	97.6%	80.0%	100.0%	78.1%
1/28/2014	128	0	128	0	0	97.6%	85.3%	100.0%	83.3%
1/29/2014	125	0	125	0	20	93.7%	86.2%	100.0%	80.8%
1/30/2014	125	0	125	0	20	93.7%	86.2%	100.0%	80.8%
2/3/2014	130	0	130	0	30	91.8%	91.2%	100.0%	83.7%
2/4/2014	137	0	137	0	0	97.6%	91.3%	100.0%	89.2%
2/5/2014	40	0	40	420	0	15.3%	88.9%	100.0%	13.6%
2/6/2014	140	0	140	0	0	97.6%	93.3%	100.0%	91.1%
2/10/2014	110	2	112	0	0	97.6%	74.7%	98.2%	71.6%
2/11/2014	83	2	85	0	180	62.4%	81.0%	97.6%	49.3%
2/12/2014	153	0	153	0	0	97.6%	102.0%	100.0%	99.6%
2/13/2014	158	0	158	0	0	97.6%	105.3%	100.0%	102.9%
2/17/2014	136	1	137	0	0	97.6%	91.3%	99.3%	88.5%
2/18/2014	146	0	146	0	0	97.6%	97.3%	100.0%	95.0%
2/19/2014	154	0	154	0	0	97.6%	102.7%	100.0%	100.3%
2/20/2014	148	1	149	0	0	97.6%	99.3%	99.3%	96.3%
2/24/2014	144	0	144	0	0	97.6%	96.0%	100.0%	93.7%
2/25/2014	150	0	150	0	0	97.6%	100.0%	100.0%	97.6%
2/26/2014	150	0	150	0	40	89.8%	107.1%	100.0%	96.2%
2/27/2014	142	0	142	0	0	97.6%	94.7%	100.0%	92.4%
2/28/2014	68	0	68	240	0	50.6%	75.6%	100.0%	38.2%
Totals	**123.1**	**0.2**	**123.4**	**26.4**	**12.0**	**90.1%**	**87.6**	**99.8**	**79.1**

Appendix F: Overall Equipment Effectiveness – Station 4

Date	Good Parts	Bad Parts	Total Production	Scheduled Downtime	Unscheduled Downtime	Availability	Performance Rate	Quality Rate	OEE
1/20/2014	74	0	74	0	0	97.6%	49.3%	100.0%	48.2%
1/21/2014	90	0	90	0	0	97.6%	60.0%	100.0%	58.6%
1/22/2014	151	0	151	0	0	97.6%	100.7%	100.0%	98.3%
1/23/2014	130	0	130	0	0	97.6%	86.7%	100.0%	84.6%
1/27/2014	109	0	109	0	0	97.6%	72.7%	100.0%	71.0%
1/28/2014	143	0	143	0	0	97.6%	95.3%	100.0%	93.1%
1/29/2014	150	0	150	0	0	97.6%	100.0%	100.0%	97.6%
1/30/2014	150	0	150	0	40	89.8%	107.1%	100.0%	96.2%
2/3/2014	121	0	121	0	0	97.6%	80.7%	100.0%	78.8%
2/4/2014	110	0	110	0	60	85.9%	81.5%	100.0%	70.0%
2/5/2014	120	0	120	0	0	97.6%	80.0%	100.0%	78.1%
2/6/2014	116	0	116	0	0	97.6%	77.3%	100.0%	75.5%
2/10/2014	110	0	110	0	40	89.8%	78.6%	100.0%	70.6%
2/11/2014	58	0	58	0	130	72.2%	49.4%	100.0%	35.6%
2/12/2014	160	0	160	0	0	97.6%	106.7%	100.0%	104.2%
2/13/2014	160	0	160	0	0	97.6%	106.7%	100.0%	104.2%
2/17/2014	125	0	125	0	0	97.6%	83.3%	100.0%	81.4%
2/18/2014	78	0	78	0	0	97.6%	52.0%	100.0%	50.8%
2/19/2014	95	0	95	0	0	97.6%	63.3%	100.0%	61.8%
2/20/2014	124	0	124	0	0	97.6%	82.7%	100.0%	80.7%
Totals	**118.7**	**0.0**	**118.7**	**0.0**	**13.5**	**95.0%**	**80.7**	**100.0**	**77.0**