Reducing Variations in a Highly Constrained Environment in Order to Increase Production Capacity

by

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Submitted to the MIT Sloan School of Management and the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degrees

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Abstract

Variations and the negatives effects it causes on production capacity and planning are topics of significant interest in the manufacturing communities. This research investigates the hypothesis that, when operating in a highly constrained environment, capacity can be gained by reducing the variations within the system.

This study tests this hypothesis through simulation, data analysis, and controlled testing on the variations responsible for limiting capacity at Vektek LLC. The variability in lead times, quality, batch ordering, and demand forecasting contributes to the Bullwhip Effect. This increase in variability will cause excessive inventory, overtime costs, unacceptable service levels, high production costs, and large lead times. This research reduces these variabilities by isolating each cause of variability and placing standard work around it, such as SOPs.

Once isolated and controlled, variations were methodically reduced, and significant capacity was gained. The research results show us that the overall variations were reduced by 26.5%. Due to this: overtime costs were reduced, late shipments were reduced by 40.0%, WIP inventories were reduced by 38.0%, and lead times were reduced roughly 22%. The total monetary value saved is estimated to be $988k and the total capacity gained was 30.8%. These results provide an initial validation that reducing the variations will increase the capacity.

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Chapter 1

1 Introduction

Capacity planning and capacity improvement is essential in all manufacturing firms across the world. Capacity is a complex mix of countless variables such as supply chains, operational and strategic management strategies, and process technology. The complexity of these relationships often results in manufacturing companies attempting to utilize technology, through smart manufacturing or Industry 4.0 methodologies, to solve their problems. Instead of focusing on technology, this research will focus on separating the complex web of these variables into their simple, foundational principles. Once isolated, we will show through simplification and iteration, that we can increase the capacity of a manufacturing plant by reducing the variability of these foundational principles.

1.1 Project Origin and Statement of Need

Vektek LLC manufactures and assembles power clamping devices for the medium and high-production industries such as automotive and aerospace. As a growing company, Vektek has traditionally hired more workers and bought more production machines to meet the growing demand. But recently, Vektek has been constrained on hiring skilled machinist because the local area has an unemployment rate of 3.2% and no longer has space in the factory to place new machines. The following research investigates how a company like Vektek can continue to increase capacity in a highly constrained environment such as limited manpower and production machines.

The Vektek manufacturing plant is located in the rural town of Emporia, Kansas. This 150 person company machines over half a million subunits a year that are assembled into 200,000 units sold per year. Vektek's competitive advantage is its ability to ship any product to their customers within 2 – 3 days of the sale. If Vektek loses this competitive advantage, they will ultimately lose market share.

As the sales have grown by 8% - 12% every year since 2011, the company has been able to meet the growing demand by adding more manpower and/or production machines. After raw material is delivered from their vendors, the material is cut, milled, turned, assembled, packaged, and shipped all in the same building. There are three main levels of inventory; raw, component goods, and finished goods. The Purchasing Department is responsible for managing the raw inventory levels. The Manufacturing (MFG) Department is responsible for managing component inventory and for manufacturing the raw material into component goods. The Assembly (Assy) Department is responsible for managing the Finished Goods Inventory (FGI), assembling the component goods into finished goods, and packaging the finished goods.

This growing demand has put a strain on the current state of operations to the point where overtime is essentially mandatory for all in MFG. Additionally, due to a lack of manpower, there is work in process (WIP) that sits in work queues and waits until there is manpower available for the machine. This results in excessive WIP levels, large batch sizes, long lead times, and excessive inventory. Lastly, Vektek has no more floor space to buy newer, more automated Computer Numerical Control (CNC) mill or lathe machines to allow for faster production. Any new machines brought in would massively disrupt current operations as multiple machines would have to be shut down as the new one is brought in.

This all results in MFG constantly feeling pressure to meet the demand placed on it by Assy. Only the FGI and short lead times for Assy keeps these constraints from greatly affecting customer sales and Vektek's competitive advantage. Vektek needs a solution to increase capacity within their constraints of limited manpower and production machines.

1.2 General Overview of Vektek Operations and Variability

In the past, much research has focused on system variability, and the bullwhip effect. This section will briefly discuss these topics before we further analyze them in the follow-on chapters.

1.2.1 Vektek Operations

Vektek Operations follow the traditional manufacturing plant process flow: Raw material through manufacturing to a component level, then an order is made to be assembled for either a customer sale or for finished goods inventory. This is summarized in the process flow diagram in Figure 1-1. The details of each process will be discussed in detailed in later chapters.

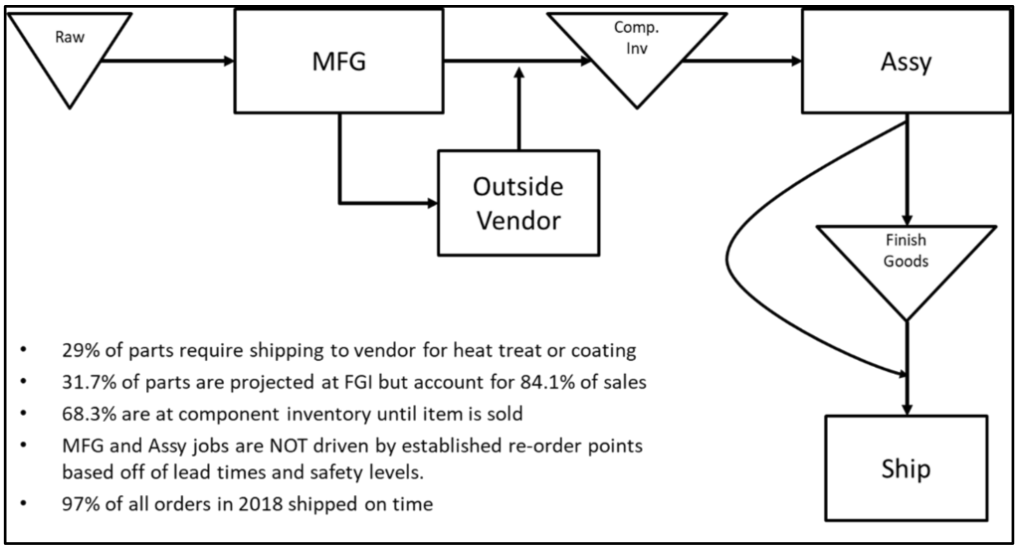

Figure 1-1: Vektek Process Flow Diagram

1.2.2 Vektek Variability

Variability is a highly researched topic that has numerable negative side effects. David Simchi-Levi's research [14] shows that an increase in variability leads to excessive inventories, larger production batches, unacceptable service level, and product obsolescence. The variability in lead times, quality, setup times, and other factors such as inaccurate forecasting and long lead times are known to contribute to the Bullwhip Effect.

Within Vektek Operations, the majority of the variability is seen in inventory ordering processes, lead times, machine setup times, and quality. Assy, MFG, and Purchasing all manage their inventory reordering methods differently. In 2018, Vektek's average lead time per job in MFG was 10.8 days while its standard deviation was 11.6 days. The average standard setup time per job was 4.81 hours while the standard deviation was 4.26 hours. Lastly, the average quality was 96.5% per batch with a standard deviation of 6.19% per batch. These variations lead to inefficient resource utilization because planning and managing become very difficult in this environment.

1.3 Problem Statement and Approach

Vektek can no longer gain capacity by hiring new employees and/or purchasing new machines. I hypothesize that by reducing the internal operational variations that Vektek can gain additional capacity in order to continue to meet a growing demand while also maintaining their competitive advantage of a 2 – 3 day delivery of all their products.

To test this hypothesis, the research will progress through four phases. The first phase will primarily be focused on observing Vektek as a whole and gaining an unbiased understanding of how all the pillars of business and engineering connect to make Vektek a successful manufacturing business. This phase has no specific goals except to gain a general understanding of the current operations.

Phase two will begin after gaining an understanding of the company. During this phase, we will orient on the problem of variability. Data collection will be ongoing and significant time will be spent with key stakeholders to gain a specific understanding to how Vektek has reached its current state of operations.

Phase three will primarily be focused on data analysis and deciding a course of action. We will analyze the data and synthesize it to the observations made about Vektek. During this phase, management inputs will be constantly sought after to ensure key stakeholder buy-in. This phase will conclude once a decision has been made on the analysis with key stakeholders involved.

After the decision, phase four will be spent focusing on implementation of the decision. Significant work will be put into ensuring that everyone understands the decisions and that it is implemented properly. Constant re-evaluation will occur to allow readjustment and refinements to prevent failure of the implementation. At the conclusion of this phase, the four phases will repeat but focusing on a new portion of variability.

1.4 Thesis Overview

This thesis is organized as follows.

Chapter 2 provides an overview of topics that are relevant to the thesis and is tailored to only include information that is relevant to operating in the highly constrained environment of our system. Chapter 3 provides a current state analysis for Vektek to gain a baseline understanding of Vektek's operations and constraints. Chapter 4 provides the methodologies of data collection, analysis, and solutions. Chapter 5 provides the results of the actions taken based off the analysis. Chapter 6 provides a conclusion to the topic of variability and provides a general overview for next steps for Vektek's operational plans.

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Chapter 2

2 Literature Review

In this chapter, we will discuss the background information that affects variability. First, we'll discuss the original causes of variability and how these limit capacities. Then, we'll introduce topics that will become our solutions to these causes.

2.1 Bullwhip Effect

The Bullwhip Effect is commonly studied through the lens of supply chains. As we apply the Bullwhip topic to Vektek, we are speaking primarily to the variations within internal Vektek Operations from the customer to assembly to manufacturing and finally onto raw material. We are not addressing the supply chain variations that exist from the Vektek suppliers and its shippers.

2.1.1 Bullwhip Main Drivers

Within supply chains and manufacturing companies, there is a phenomenon known as the Bullwhip Effect. This is where demand information gets systematically distorted to be larger and more variable as you move up in the supply chain from the original source of variability, the customer. This Bullwhip Effect was first studied in 1961 by Forrester and has since become a phenomenon taught to many business schools worldwide in the form of 'the Beer Distribution Game' by John Sterman. This game is an exercise to see firsthand how the supply chain factors increases the variability and the negative effects of this variability.[9]

This Bullwhip Effect has been studied by many industries and companies, to include Procter & Gamble (P&G) and Hewlett-Packard. P&G noticed that even though their retailer's sales were stable, the orders of the retailer to the distributor fluctuated much more than the customer's orders. Then, the distributor's orders to the manufacturer varied even more than the distributor's. In Figure 2-1, David Simchi-Levi provides a simple graphic in his book, *Operations Rules,* where he illustrates a simple three-stage supply chain and the associated bullwhip effect as a function of time. We see in the graph that as time progresses and as you move up the supply chain, the order not only gets larger, but the variability continues to rise.[14]

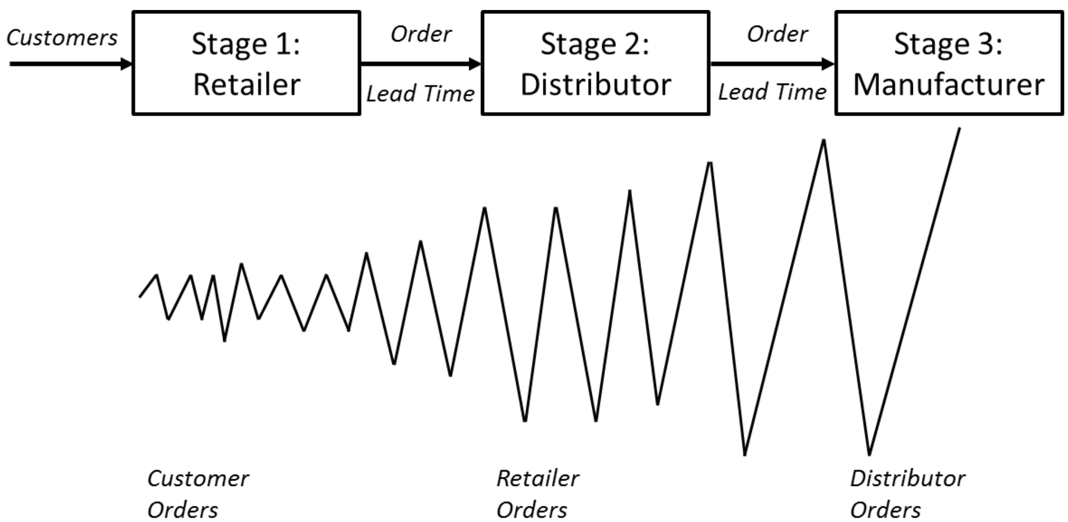

Figure 2-1: Multi Stage Supply Chain and Bullwhip Effect

To understand all the variables that affect the bullwhip, we need to put ourselves in the minds of the Distributor. At Stage 2, we receive orders from the Retailer and then in turn, place an order to the Manufacturer. To determine the order size we place to the Manufacturer, we must first consider the Retailer's current demand. Then, we consider the variability during the lead times both within our own system and the Manufacturer's lead times to meet that demand. As the lead time gets longer, the same variability is subjected to a longer period and thus greater total variability. Therefore, there is an associated increase in variability that must be accounted for.

Due to these lead time factors, we need to account for the current demand, and we must also forecast the Retailer's demand. Forecasting demand, more times than not, is inaccurate. Therefore, as our inaccurate forecasts of the Retailer's demand is realized, we will have to change what we order to the Manufacturer and order a larger batch size to account for our inaccuracies. This increases the variability imposed on the Manufacturer even more. As the Retailer is ordering large batch sizes due to their own bullwhip factors, we will see a period of high demand for a product followed by periods of no demand. This also results in a perceived increase in variability.

These factors of demand forecasting, lead times, and batch ordering are even further amplified by a lack of communication that often exists between each stage. With all these factors affecting variability, the decision makers have a hard time planning and often results in more and more inefficiencies. The system quickly spirals out of control resulting in the Bullwhip Effect.

2.1.2 Bullwhip Solutions

The resultant Bullwhip Effect can be countered with the reduction of uncertainty, reduction of variability, and lead time reduction. According to Schemi-Levi, reducing uncertainty throughout the entire supply chain will result in naturally lowering the variability [14]. Communicating more, sharing demand data, and synthesizing demand forecasting and ordering techniques will all minimize wrongful assumptions that lead to poor decision making and it will help encourage information flow between different stages of production.

Naturally, reducing the variability within the production system will also result in reducing the total variation. Within manufacturing systems, the variations are often found in lead times, machine changeovers, and quality. Creating standardized work, a topic discussed in Section 2.5, will reduce the variability of all three of these factors.

Lastly, reducing both the variability and length of lead time will have a positive effect on the reduction of the Bullwhip. In this context, the variable lead time is the variable lead times between different productions of the same stock keeping unit (SKU). Additionally, reducing the total lead time of these variations will clearly have a positive effect in reducing the total variations. We will discuss more of lead time reduction in Section 2.5.

2.2 Periodic Review Policy

For most manufacturing companies, managing the inventory can be very difficult without an inventory policy to establish inventory levels. For the purpose of our discussion, we will only discuss what is commonly referred to as the Periodic Review Policy. The purpose of this policy is to balance the cost of having too much inventory on hand versus not having enough.

The Periodic Review Policy establishes the safety inventory level and inventory reorder points based on the statistics of random demand. The model is derived from a few assumptions that the inventory is never obsoleted, there is an unlimited number of replenishments, demand occurs during the replenishment period, and the raw material required to begin the reorder process is on hand at the moment of reordering.

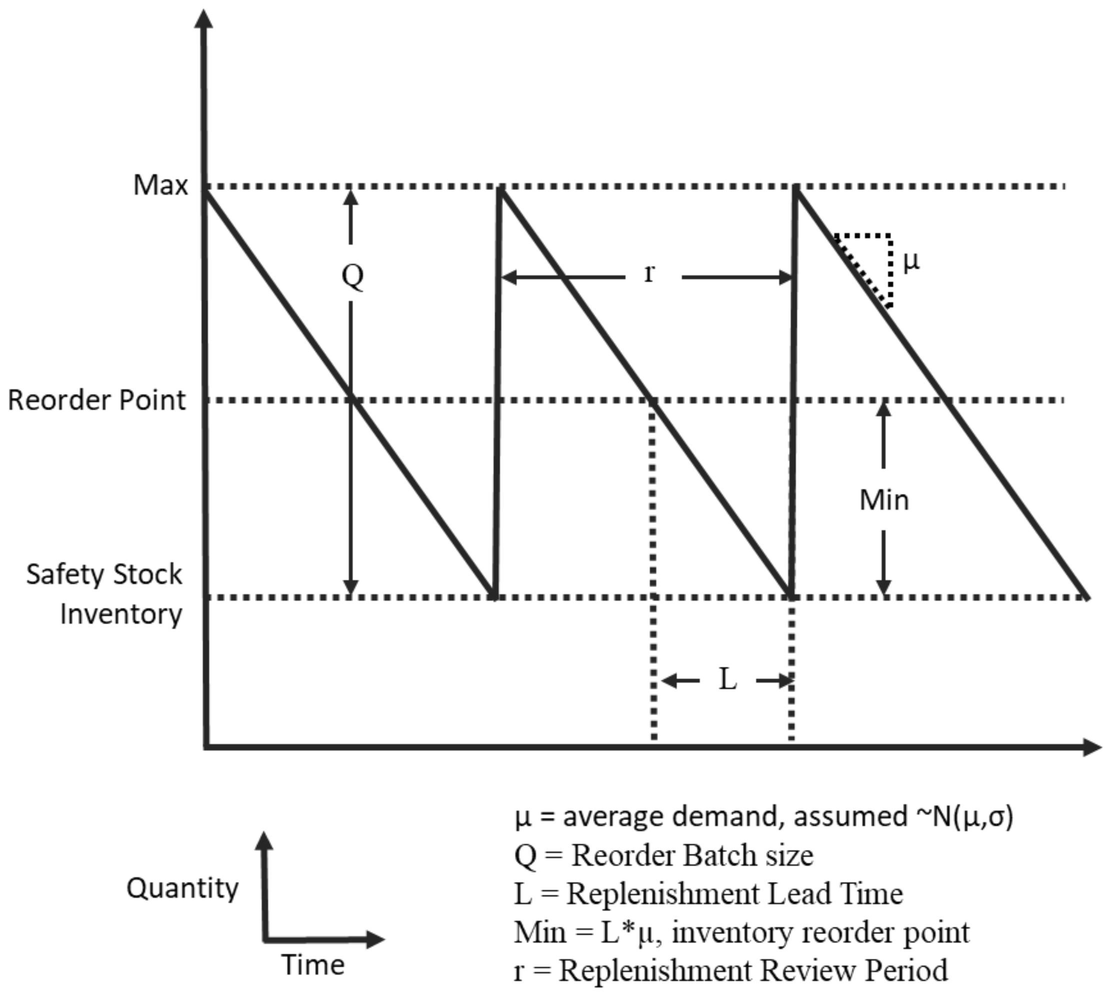

Figure 2-2: Inventory Cycles

Figure 2-2 shows the typical inventory cycle. As time progresses, inventory is consumed by demand [assumed to be~N(μ,σ)], inventory is re-ordered (Q) and eventually arrives into inventory after a replenishment lead time period (L). Upon arrival of the replenishment order (Q), the inventory reaches a max level and then continues to be depleted at the consumption rate until the re-order point has been reached again. This cycle is repeatable for the foreseeable future.

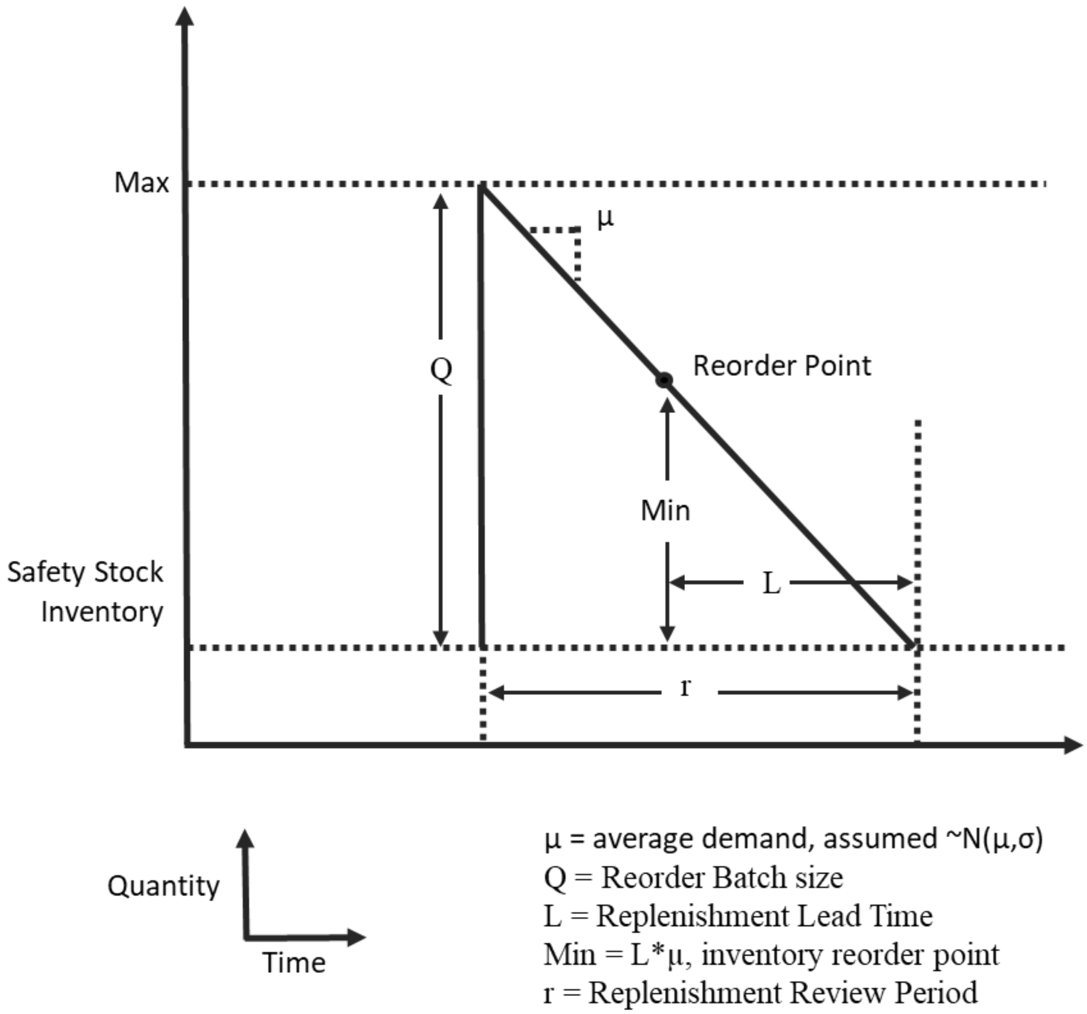

Figure 2-3: Single Inventory Cycle

For simplicity, Figure 2-3 above shows a single inventory cycle with a given demand [assumed to be~N(μ,σ)], a predetermined batch size (discussed in the following section), lead time (L), and review period (r), where 'r' is the interval of time that the user takes between conducting an inventory evaluation to determine if they should order more inventory or not. Graves and Willems (2019) show us that if we assume that demand is normally distributed with a given customer service level (z-score), then we can determine the safety level to be given in Equation 2-1.

$$Safety\ Stock = z * \sigma * \sqrt{r + L} \qquad (2\text{-}1)$$

Additionally, utilizing trigonometry from the graph, we see that the reorder point above our safety stock is just the length of the replenishment period multiplied times the average daily consumption. For our discussion, we'll define that value as *min* and is seen in Equation 2-2.

$$\text{Min} = L * \mu \tag{2-2}$$

$$Reorder\ Point = Safety\ Stock + min \tag{2-3}$$

Adding Equations 2-2 and 2-3, we establish our reorder point equation that will minimize the total stock on hand. This minimizes the inventory on hand because the replenishment batch arrives the moment the quantity on hand reaches the safety stock level. After which, there will be a period of no WIP before the quantity on hand reaches the reorder point again. Once it reaches the reorder point, more inventory will be ordered, and the cycle continues as previously outlined.

From these equations, we can determine the average on hand inventory during the average inventory cycle. The inventory that is constantly being depleted is commonly known as the cycle stock. Cycle stock at its max is just batch size (Q), and at its minimum is 0. Assuming that the demand average is constant during the cycle, the average cycle inventory on hand over the cycle is just half the batch size. If safety stock is never depleted, the average inventory during the cycle is safety stock plus the average cycle inventory.

$$Average\ Inventory = \frac{Q}{2} + Safety\ Stock \tag{2-4}$$

At any given time, we will have some amount of cycle stock on hand, safety stock, and perhaps WIP if the quantity on hand is below the reorder point. Due to this, Graves and Willems say that we should expect the inventory level to be equal to the sums of the cycle stock, min, and safety stock, seen in Equation 2-5. From this equation, we see that the dominating factor we can control is the lead time. In order to reduce the safety and min, it is essential that the lead time is reduced. [19] Lead time reduction will be discussed in Section 2-5.

$$Inventory = r\mu + L\mu + z\sigma\sqrt{r + L} \tag{2-5}$$

2.3 Efficient Order Quantity

2.3.1 Determining the Efficient Order Quantity

The Efficient Order Quantity (EOQ) is a highly researched topic to address the business challenges of balancing demand uncertainty and capacity limits. Ron Yuan and Stephen C. Graves's research (2015) says that because there is an uncertain demand signal and a production capacity limit, companies often manufacture their SKUs in a batch that will meet both the current demand and a projected future demand.[4] A single batch for machine shops consists of multiple units of the same SKU that will go through a series of work stations. At each station, the machine will have to be setup, or configured, with the proper tooling, fixtures, and CNC program before the machinist can begin to produce the batch. Once the machine is setup for the SKU, the machine produces units until all the units in the batch are complete. At this point, the batch is moved to the next work station and the machine will be setup again for the next SKU batch.

During this setup time, the machine must be shut down and can't produce any product. Therefore, increasing the batch size will reduce the total number of setups required during a given period for that SKU, which will reduce the overall workload on the work station. But the larger the batch size, the longer the processing time ,which results in less fluid work flow and an irregular arrival of the batch to each work station. This increase in arrival variability will result in production variability. Thus, we want to reduce the batch size to reduce the variability.

EOQ is a method to establish the batch size on optimal costs associated with all the variables mentioned. A manufacturing company will want to minimize the annual cost of the SKU by finding an optimal point between the holding cost of the inventory and the setup cost. To determine the holding cost, we just need to multiply the average inventory level by the holding cost of that SKU. To find the setup cost, we multiply the number of annual setups by the setup cost (s). The total number of setups can be easily calculated as the total annual demand divided by the batch size. This relationship is seen in Equation 2-6 where Q is the batchsize, d is the annual demand, and 'h' is the holding cost factor.

$$Annual\ Cost(Q) = s\left(\frac{d}{Q}\right) + h\left(\frac{Q}{2}\right) \tag{2-6}$$

Utilizing Equation 2-6, we are able to determine the optimal batch size, Q*, by taking the derivative of the equation and solving for Q*. This is the most common equation of EOQ and is seen in Equation 2-7.

$$Q^* = \sqrt{\frac{2sd}{h}} \tag{2-7}$$

But as Yuan and Graves point out in their research, there are more factors to consider when looking at the entire manufacturing process. There is the holding cost associated with every level of inventory and even a holding cost associated with WIP. [4] The equation for Vektek MFG Department then changes from Equation 2-7 to equation 2-8 below. A graphical representation of this equation for a Vektek component SKU is seen in Figure 2-4.

$$Cost(Q) = Setup\ Cost + Holding\ Cost_{raw} + Holding\ Cost_{Comp} + Holding\ Cost_{WIP} \quad (2\text{-}8)$$

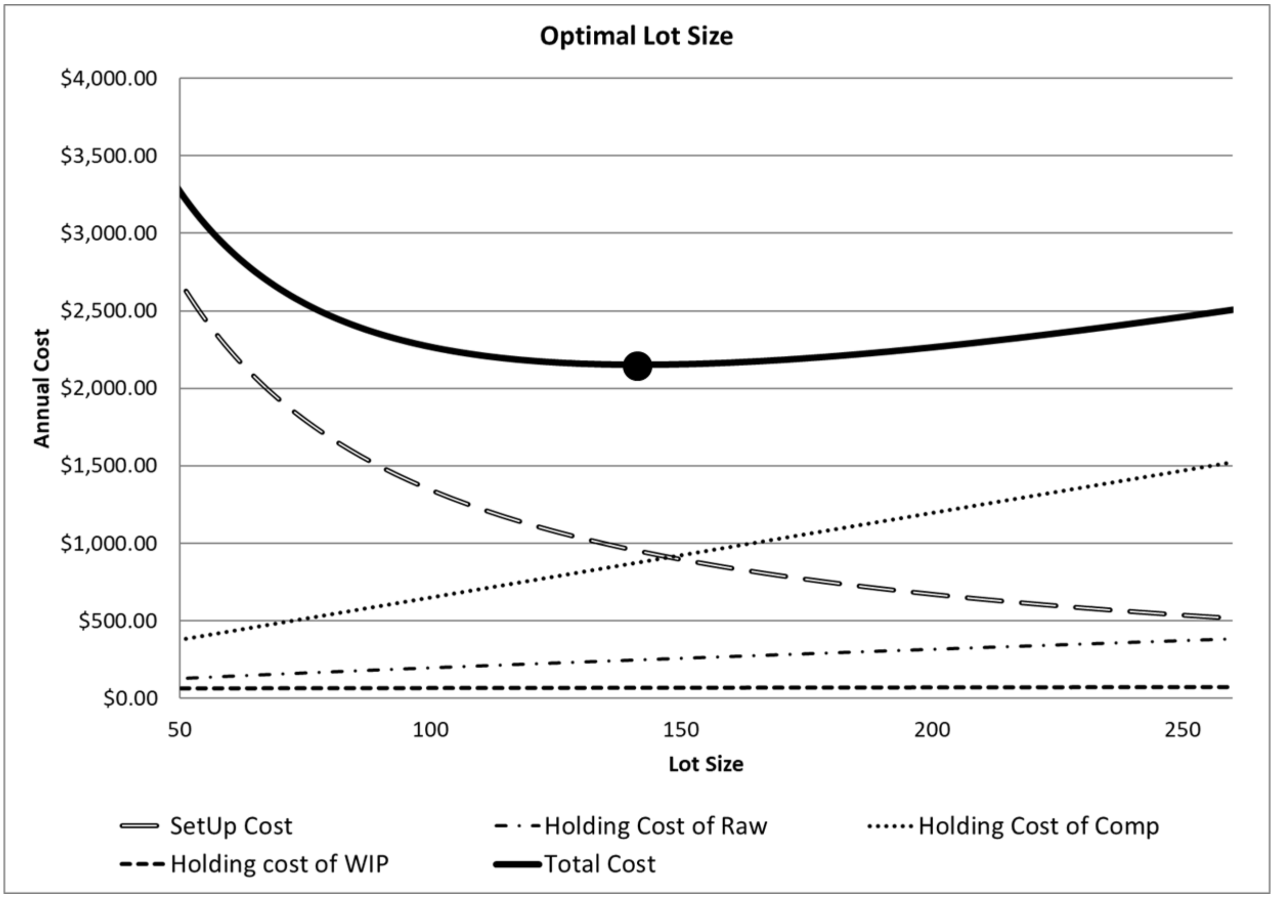

Figure 2-4: EOQ for a Vektek SKU

Analyzing Figure 2-4, we see not only is the objective function flat around the optimal point, but that the two dominating factors are the setup cost and the holding cost of components. This is due to the relative cheap cost of raw material and the short period that it is WIP. This is good news as it simplifies the problem if the goal is to just be close to optimal instead of perfectly optimal. If this is the case, then comparing the setup costs to the component holding cost will result in achieving the results we're looking for.

2.3.2 The Impact of Batch Sizing

Determining the proper batch size plays a huge impact in manufacturing. Reducing the batch size will decrease the overall lead time required to complete processing the batch. This will result in less variability of workload arrivals and less batch processing times which reduces our overall waiting time, but increases the relative time spent on setups. Reducing overall waiting time and processing time will reduce the required lead times, which will reduce inventory levels even more.[7]

Utilizing the above SKU example and Equation 2-4, we are able to see the relation, in Figure 2-5, of the safety stock and batch size to overall inventory. We see that at first, safety stock has a huge impact, but eventually the batch size overtakes as the dominating factor for determining the average inventory required on hand. As the batch size increases, so does safety stock, but not at the same rate or impact that batch sizing has. This means, that if we want to reduce the overall inventory, reducing batch size is critical. But as we will see in Section 2.5, process improvement must occur to allow for the reduction of the batch size.

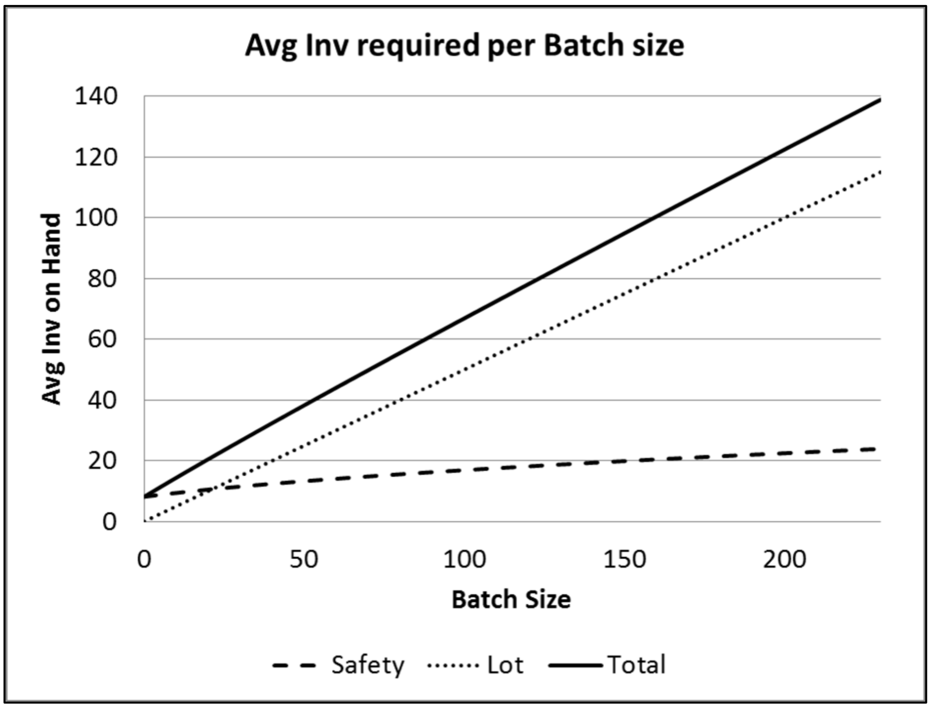

Figure 2-5: Average Inventory required as batch size changes

2.4 Quality

According to the *Consumer Reports* in 2018, Toyota and Lexus (luxury brand of Toyota) were ranked the top two most reliable car brands amongst the top 29 most popular brands. Additionally, they have taken the top two ranks for the past six straight years. Additionally, Toyota produces 15 of the top 20 most reliable vehicle models over the past 10 years.[12]

So, how does Toyota make such high-quality products? Toyota learned long ago that solving quality problems at the source saves both time and money downstream. By continuously solving problems at the source, productivity soars even though you usually must stop production to solve the problem. Taiichi Ohno said, “Correct a mistake immediately – to rush and not take time to correct a problem causes work loss later.”[11]

Toyota has built a culture that allows the manufacturing process to slow down to fix the root cause of the problem. In order to fix the problem, there must be standard work. Standardized work is a key to building quality. Whenever a defect is discovered, the first question asked should be, “was standardized work followed?” Without standard work, quality improvement can never be achieved across the entire system as any improvement will be short lived.[10]

After Toyota establishes standard work, they develop a culture to stop to fix the problem immediately. In-station quality is much more effective and less costly than inspecting and repairing quality problems after the fact. Thus, they have built in sensors and production tools to detect any deviation from standard. Their classic example is an *Andon Cord* that alerts the first line supervisor of a defect. Once alerted, the supervisor assembles a team to fix the problem before the product is passed downstream. After fixing the problem, the team does a root cause analysis to determine the source of the defect and then they put procedures in place to ensure that the problem can never occur again. Finally, they update the standards and use standard work as a countermeasure to quality problems.[1]

A local Toyota plant manager told Jeffery Liker one day, “*Andon* only works when you teach your employees the importance of bringing problems to the surface so they can be quickly solved. Unless you have a problem-solving process already in place and people are following it, there’s no point in spending money on fancy [*Andon*] technology.” The manager is pointing out that both the people and process must be in place before you should expect any quality improvement to occur.[10]

2.5 Process Improvement Tools

The process improvement tools discussed are handpicked as the best to help reduce the predefined variations within a machine shop. Furthermore, these tools are designed to help the managers and employees alike in improving their work conditions to make them more productive.

2.5.1 Lead Time Reduction

As we have seen in the periodic review model, lead time is one of the main drivers that we can control to determine the inventory levels. The longer the lead times, the higher the safety stock and WIP.. Any attempt to reduce the inventory levels will have to address reducing the lead times.

For Vektek manufacturing, the planned lead times for a single SKU batch will be the processing time at each work station plus the queue time at each station. This relationship is seen in Equation 2-9.

$$Lead\ Time_{batch} = Total\ Processing\ Time + Total\ Queue\ Time \tag{2-9}$$

The processing time for the batch at each work center is just the machine setup time and the actual cycle time of the batch. The total processing time will be the sum of all the work centers. This is seen in Equation 2-10.

$$Total\ Processing\ time = \sum_{WC}[(Cycle_{WC} * batch) + Setup\ Time_{WC}] \tag{2-10}$$

The queue time, or wait time, that a batch undergoes is first determined by the amount of WIP that is in front of the batch. The batch will then have to wait for every setup and cycle time of all the WIP. This equation is similar to the total processing time, but instead of summing each work center, we sum all the WIP.

$$Total\ Queue\ Time = \sum_{WIP}[Setup\ Time_{WIP} + (Cycle_{WIP} * lot_{WIP})] \tag{2-11}$$

Substituting Equation 2-10 and 2-11 into Equation 2-9 we see that the variables that are easily within our control are WIP, setup times, and lot sizes. As we decrease any one of these variables, we will be able to reduce the overall lead times. Reducing these will be discussed in follow-on sections.[3]

2.5.2 5S

5S is a tool that volumes have been written on. In short, according to Productivity Press, 5S is the foundation of all process improvement[6]. It is a simple and universally powerful tool that allows the workplace to be free of clutter, organized, and clean. Research shows that the five pillars of sort, set in order, shine, standardize, and sustain have proven to yield higher productivity, produce fewer defects, meet deadlines better, and provide a much safer place to work.[6] In Art Byrne's book *The Lean Turnaround*, he states that 'In order to create the basic discipline required to implement Lean, you will first have to make 5S second nature for everyone in your organization.'[1] The value and importance of 5S cannot be stressed enough. The value of standardizing in building a teamwork environment will be further discussed in Section 2.6.

2.5.3 Setup Reductions

Taiichi Ohno, the father of Just in Time manufacturing, famously said in his book, *Toyota Production System*, that "Setup was regarded as an element that reduces efficiency and increases cost. [Setup reductions] are an absolute requirement for the Toyota production system."[11] Art Bryne said, "Setup reduction is the core foundational level of Lean…Therefore, one of the first goals is to cut your setup times and keep reducing them until they are all in single digits."[1]

Nearly every manufacturing company requires some type of setup or machine changeover. Having long setup times is expensive and leads to increased batch sizes.. Reducing batch sizes and lead times is all but impossible if the setup times are not consistent and minimized. In the figure below, we see an example of the few setup reductions (often called SMED) that Wiremold was able to achieve in just a single week per equipment type.

	Setup Time (mins)		
Equipment Type	**Before**	**After**	**% Reduction**
Rolling mill	720	34	95%
150 ton press	90	5	94%
P.M. punch press	52	5	90%
Hole cut on mill 1228	64	5	92%
2.5" extruder	180	19	89%
Injection modler	120	15	88%
Average Setup Reduction = 91%			

Figure 2-6: Wiremold SMED Results[1]

SMED, single minute exchange of dies, is a simple, inexpensive process made famous by Shigeo Shingo. In his book, *A Revolution in Manufacturing: The SMED System*, he lays out the three-step process to SMED.[13]

The most important step is the first one where you first define each process of the setup as either an external or internal process. The external processes, like staging inspection equipment or inventory, can be done while the machine is running and should be completed before the previous job is complete. The internal processes, like tool changeovers or uploading the new CNC program, can only be done while the machine is stopped. Additionally, during this step, standardizing the setup process is critical to sustaining the improvements. The first step often results in an immediate 30 to 50 percent setup reduction and only requires establishing a standard operating procedure after categorizing each process.

The second step is to reexamine the internal processes and to find ways to convert these internal processes into external processes. Once it becomes an external process, they can be completed while the machine is running the previous SKU, further reducing the total setup times.

Step three is to streamline all aspects of the setup operation to further reduce the time of each process. SMED is never complete as all three steps should constantly be reevaluated and revisited.

SMED has many benefits.. Once setups are reduced from hours to minutes, the company can drastically reduce the batch size. By reducing the batch size, the company gains flexibility by allowing them to meet the ever-changing customer needs without the expense of excess inventory.[13] Additionally, smaller batches results in less lead time and less wait times, as previously explained in the lead time reduction section.[7] Lastly, shorter setups reduce downtime, which increases productivity.

2.5.4 Overall Equipment Effectiveness

Tim Collins says in his book, '*Good to Great*,' that 'Good-to-great organizations think differently about technology and technological change than mediocre [companies]…Good-to-great companies use technology as an accelerator of momentum.' The evidence is overwhelming that technology can propel a company forward in ways that were previously unimagined.[2] Utilizing modern technology, companies are now able to quickly determine where their inefficiencies are through a tool called, Overall Equipment Effectiveness (OEE).

OEE is the gold standard for measuring manufacturing productivity. Vorne Industries states, “Simply put – [OEE] identifies the percentage of manufacturing time that is *truly* productive.” [18] OEE is considered by most to be a manufacturing best practice as it is a technique to determine where the underlying losses are so that you can systematically improve your entire manufacturing system.

OEE is the result of measuring three distinct areas: Availability, Performance, and Quality. Each metric is rated as a percentage and once multiplied by each other, you can determine the OEE for the particular machine or process. A perfect OEE score of 100% means that you are manufacturing only good parts (quality), as fast as possible (performance), with no stop time (availability). The world class standards are seen below in Figure 2-7.

Category	Percentage
Availability (A)	90%
Performance (P)	95%
Quality (Q)	99.9%
OEE (A x P x Q)	85%

Figure 2-7: World Class OEE[18]

The first metric is Availability. Equation 2-12 shows us that availability measures the actual run time versus the planned production time. This category captures all the stoppages that are both planned and unplanned to include equipment failure, machine setups/changeovers, and machine adjustments. Any loss in this category would direct the manufacturers to better focus on procedures such as SMED or investment in new/more tooling.

$$Availability = \frac{Run\ Time}{Planned\ Production} \tag{2-12}$$

Performance is a measure of how fast the machine produced the product once the machine begins production and is compared to the ideal conditions. This metric is often overlooked and assumed to just be an unimprovable part of the manufacturing process. Small stops such as periodic cleaning or obstructed product flow are hard to measure, but performance helps capture this information. Additionally, reduced speed due to worn out tooling or operator inexperience is also captured in this metric. Any loss in this category would direct the manufacturers to focus on areas such as better tool life or improving operator efficiency.

$$Performance = \frac{Ideal\ Cycle\ Time\ per\ Part * Good\ Part\ Count}{Run\ Time} \tag{2-13}$$

Quality is a measure of the good parts produced,and is the ratio of parts made correctly the first time to the total parts, seen in Equation 2-14. As expected, this metric accounts for all the parts that are not made to specifications during both the machine setup process and during the processing time. Solutions to these problems have been discussed in the quality section.

$$Quality = \frac{Good\ Parts}{Total\ Parts} \tag{2-14}$$

Utilized properly, OEE is an incredible tool to help direct efforts to increase productivity. With modern technology and the push for Industry 4.0 implementation, gathering data for the OEE has never been easier. There are countless add-ons and new machine software that automatically collect the data, such as MachineMetrics Inc. and Vorne Industries. Utilizing OEE as a tool to direct problem solving will increase the productivity and decrease the variability throughout the entire manufacturing plant.[18]

2.5.5 Flexible Operations

Within the context of flexible operations, there are two main types of flexibility that a manufacturing system can achieve. The first type is manpower flexibility. This will be discussed in greater detail in Section 2.6. The second type, and the primary topic this section, is process flexibility.

William Jordan and Stephen Graves (1991) said, “Increasing manufacturing flexibility is a key strategy for efficiently improving market responsiveness.” Car manufactures historically deal with a difference between forecasted demand and actual demand to be ± 40%. Process flexibility is one key strategy they utilize to deal with this uncertainty. The benefits of process flexibility are obvious, but how much is needed and where, is not.[5]

Figure 2-8 is an illustration of a system with zero flexibility and a system that is fully flexible. With the first system, there are five products that are made by dedicated plants that can only make that one product. When demand for Product A rises, only Plant 1 can surge to meet the demand. If demand for Product A exceeds Plant 1’s capacity, then there will be a reduction in expected sales because the system cannot meet demand. Conversely, if demand for Product B goes down at the same time, then Plant 2 has excess capacity, but it cannot help Plant 1 to meet this demand.

One solution is to gain flexibility so as demand shifts, the system can capitalize on the reduction of demand in one plant to make up for the increase in demand in another plant. The Full Flexibility system in Figure 2-9 shows a system where all products can be made by any plant. As before, when Product A goes above Plant 1's capacity, any plant (2-5) will be able to absorb some of the demand to lessen burden on Plant 1. This leveling of the workload is one of Toyota's 14 Management Principles.[10]

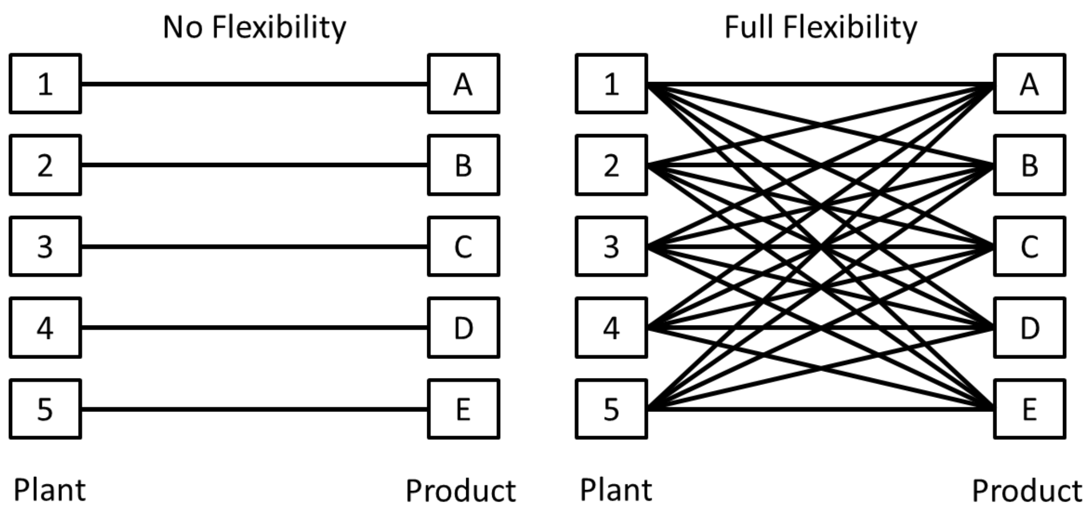

Figure 2-8: No Flexibility and Full Flexibility Systems

A full flexible system is very costly and might not even be achievable. So we ask the question, can the benefits of full flexibility be achieved with less-than-full flexibility? Jordan and Graves provide an answer.

The key is that gaining a little flexibility will achieve similar benefits of the full flexibility system as long as the added flexibility is in the right places. The concept Jordan and Graves developed is called *chains.* As *links* connect one plant to a product, adding more *links* creates a *chain* where a path can be endlessly traced. A *chain* is a group of these *links* that products and plants are all connected, both directly and indirectly. Figure 2-9 shows a 1 chain system and a 2 chain system.[5]

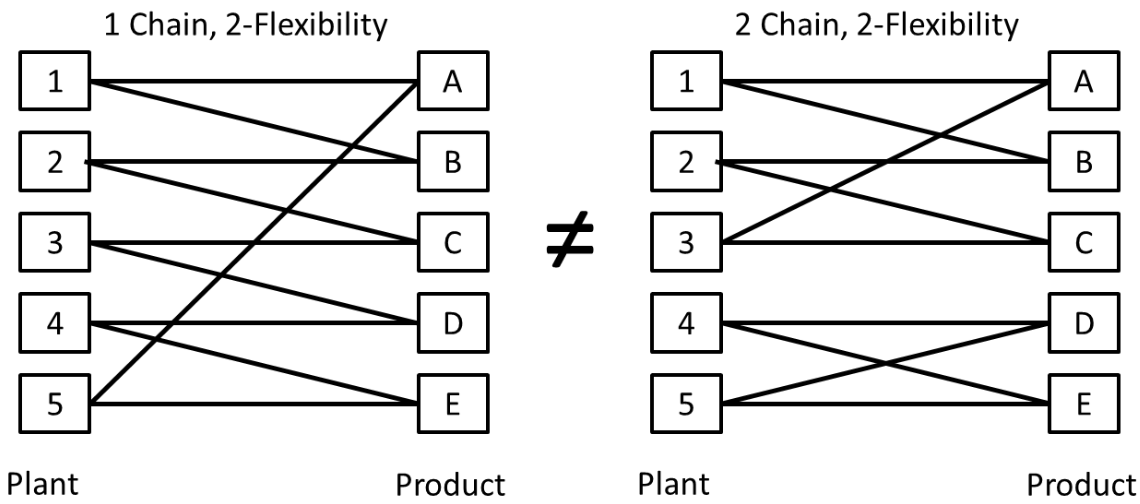

Figure 2-9: 2-Flexibility, 1 and 2 chains

We see that both systems have 10 total links. In the 1 chain system, we see that all products can be made by 2 plants and all plants can make 2 products. The chain is an endless loop and all the products and plants are connected, both directly and indirectly. The 2 chain system shows Products A, B, and C, are part of one chain and Products D and E are a separate chain[1]. Jordan and Graves make an important observation that, although these systems are better than the no flexibility system, the added benefits of both systems are not the same. The 1 chain system has significantly more benefits than the 2 chain system. This is because the longer the chain, the more opportunities to shift capacity to meet the changing demand. Thus, there is a greater opportunity to rebalance the workload.

The goals of chaining is to minimize the number of chains and to lengthen the chains. This is because chaining allows all products within the chain to share the total chain's capacity to meet the total chain's demand. As long as the total capacity is greater than the total demand, the system will be able to meet the demand. To convert the 2 chain system into a 1 chain system, Plant 3 will need to stop making product A and make Product D while Plant 5 will need to make Product A instead of Product D. The result will be the same number of *links*, but a single, longer *chain*. Jordan and Graves summarize their key observations below:

1. Adding [flexibility] increases both expected sales and capacity utilization

[1] The benefits of a chain can only be realized if it is a closed loop.

2. Flexibility achieves these benefits by i) allowing the product mix in plants to be changed during production in response to unforeseen demand variations and by ii) better balancing expected demand with capacity.
3. In contrast to flexibility, adding capacity increases expected sales but decreases expected utilization. Subtracting capacity has the opposite effect.
4. Adding flexibility can, to some extent, be substituted for changing capacity to reach sales or capacity utilization goals.
5. The benefits of flexibility remain significant as long as total capacity is roughly balanced with expected demand.
6. Once a plant-product chain has been created, a little more flexibility may have some benefit. This flexibility should be added in a way that better balances the assignment of products to plants, and/or that creates chains. However, there are diminishing benefits to adding more flexibility within the chains.[5]

2.6 Successful Organizational Structures

There are countless articles, books, and research papers written around organizational structures that are essential to business success. Within the Vektek context, we will only discuss building a teamwork environment, cross training, and operating with slack. These all focus on the employees and can be summarized with a quote from Zeynep Ton, "Good Companies provide jobs with decent pay, decent benefits, and stable work schedules. But more than that, these companies design jobs so that their employees can perform well and find meaning and dignity in their work."[17]

2.6.1 Building a Teamwork Environment

Taiichi Ohno said, "Teamwork is everything." In his book, *Toyota Production System*, he compares the manufacturing line to a competitive rowboat of eight athletes. If all eight athletes were to row at their own pace, the boat would essentially go nowhere. But, if you were to synchronize the rowers on the right into one team and the rowers on the left into one team, you may be able to go forward, but not very efficiently. It is only when the entire boat is operating at the same pace and rhythm that you are able to go forward and compete with the other boats. Once you're in competition with the other boats, it is both the cumulative strength of the team and the ability of the team to work together that will determine if you are victorious or not.[11]

In manufacturing, there can easily be between 10 – 15 individual workers responsible for converting the raw material into a finished good. Like the boat, if the manufacturing system isn't working together as a team, you may still be able to produce products, but it will be woefully inefficient. The key is to build an environment where the members can work as a team.

Creating an environment for teamwork to prosper should be one of the first steps in building a team. If everyone is working alone, or physically can't work together, then teamwork simply can't exist. To change the behavior of the people within the environment, we must first change the environment to drive new behavior. Specifically, we will discuss creating standardized work, utilizing technology to allow teamwork, and developing production teams.

In the book, *The Toyota Way*, Jeffery Liker lays out the 14 principles that have made Toyota successful.[10] One of the principles is solely dedicated to creating standardized work. Liker said it best when he said:

> *Today's standardization…is the necessary foundation on which tomorrow's improvement will be based. If you think of 'standardization' as the best you know today, but which is to be improved tomorrow – you get somewhere. But if you think of standards as confining, then progress stops.[10]*

A system simply cannot be holistically improved if everyone is doing their own version of the same work. If a system doesn't have standard work, any improvement will only be short lived and will just be a short period of improvement. Once the system is standardized, any improvement in the standardized work will be felt throughout the entire system for an indefinite amount of time. This is achieved through 5S and standard operating procedures (SOP) in areas such as machine change overs, inventory management, and quality control gates.

SOPs enable teamwork in multiple ways. The biggest benefit is that it increases communication by creating a common language and enables implicit communication. For example, if two machinists were to work together to conduct the machine changeover, they will likely spend the majority of the time just trying to figure out which method should they follow…one worker's method of changeover or the other's. If they both do it differently, the system simply doesn't allow for efficient teamwork. But if they both do it the same way due to SOPs, then they can seamlessly work together and very little verbal communication will need to occur as both workers will know the procedure, from beginning to end. By removing potential confusion for new employees, SOPs enable new employees to quickly begin to contribute to the teams because there will be only one way to do the task instead of having been shown multiple ways to do the same task.[1]

Utilizing technology is a great method to enable teamwork. At Toyota, they can use a simple technology they coined the *Andon Cord*. This allows the worker to signal for help when a problem arises. In addition to the *Andon Cord*, a noise that is specific to that worker will play for the first line supervisor to hear. This allows the company to quickly provide extra resources to the problem area. After the problem is fixed, the extra resource, usually the worker's supervisor can be utilized elsewhere to help other workers. This system works because there is standard work, the employees are cross trained, and there is slack in the system.

The last technique we will discuss in building teamwork is to actually create production teams. Harry S. Truman said, "You can accomplish anything in life as long as you do not mind who gets the credit."[2] Creating the teams has to be deliberate for the team to exist. Both Simchi-Levi and Bryne encourage their readers to organize the team into a product line. In this way, the entire team is responsible for the successes and failures of the production.[10,14] Additionally, having a team gives employees leadership opportunities to grow and gain more purpose in their job – a key dimension of creating and retaining great employees according to Zeynep Ton.[17]

Bryne said, "To change the people, change the environment."[1] Simchi-Levi encourages his readers to physically change the environment by orienting the machines to allow the workers to seamlessly work together. This is achieved most commonly by arranging the machines into a U-Shape production line.[14]

2.6.2 Cross Train

"Cross-training helps companies satisfy customers, employees, and investors all at the same time," according to Zeynep Ton. Cross training helps satisfy customers because, as we will see, it allows the company to rebalance the workforce to areas of temporary high demand. Cross training provides employees with self-esteem as they are working in more parts of the value added processes. And it will satisfy investors because a cross trained workforce has proven to be cost effective as the company is able to get greater productivity out of its employees and to have higher quality.[17]

In an environment where demand is variable, having a workforce that is one dimensional and unable to move from one job to the other is not appropriate. As demand shifts, managers need to be able to shift the workforce towards the areas where the demand is higher. Cross training allows the managers to balance the production line which results in a higher utilization and increases the throughput of the stations. Additionally, Schimi-Levi provides evidence that a cross trained force working in a team has the added benefit of smoothing out the workflow, thus reducing the variability.[14]

Much like we discussed in the section about process flexibility, worker flexibility doesn't have to be achieved by having everyone able to do everyone else's job. A small investment in worker cross-training achieves almost all the benefits of full-skill cross training. Schmi-Levi provides a simple figure of his research to show the results, Figure 2-10.

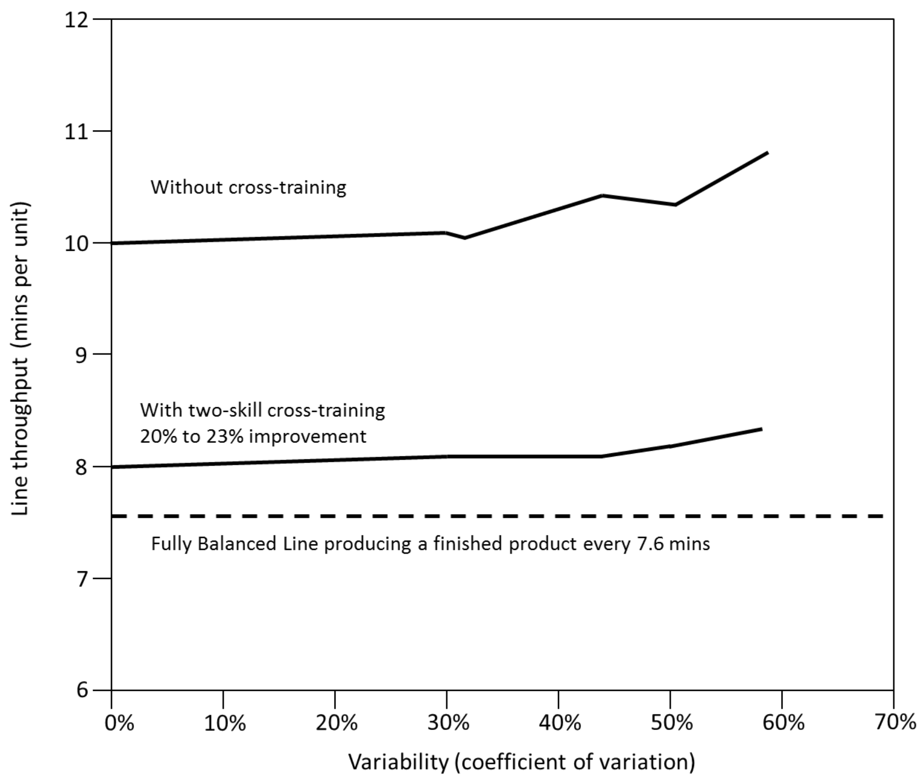

Figure 2-10: Production Line Throughput as a function of variability

In the top line for a non-cross trained workforce, we see that the throughput remains relatively unchanged until the variability reaches 30%. Afterwards, it rises to 11 minutes by 60% variability. But, when the work force was trained to allow everyone to work two jobs instead of one, we not only see that the throughput has been reduced by 20%, but that the throughput remains stable regardless of the variation. Lastly, to his point, if every worker was fully cross trained, the benefits would only have been a further reduction to 7.6 minutes of throughput. Therefore, we can conclude that if adding flexibility is wisely done, one can achieve near full benefits of a fully cross trained force with minimal cross training investment.[14]

Cross training has proven to give employees higher self-esteem as it gives them a greater sense of making a difference as they get more purpose out of their jobs. Making a difference and using a variety of skills leads to greater job satisfaction and pride in their work. Workers with greater job satisfaction and pride will produce higher quality parts. Producing higher quality parts and employees working more on value added steps increases the productivity of the workforce. All these benefits are the result of the simple concept of cross training.

But as we discussed earlier, a company cannot reap the benefits of cross training if there is not standard work. Cross training employees becomes difficult if not all but impossible if standard work or teams do not exist. This is just more evidence that supports that standard work is the foundation of all process improvements.[17]

2.6.3 Operate with Slack

Operating with slack is perhaps the most important foundational pillar a company must achieve in order to begin investing in their employees with cross training, continual educational programs, and process improvements.

Eliyahu Goldratt said in his famous book, *The Goal*,[5] that employees are uncomfortable if there is no work to do and that managers want to get 100% worker utilization in order to be seen as productive. But employees who are having a hard time to just simply complete their tasks on time will rarely find the time to stop and think about how to improve their system. Even if they can find the time to think about it, they will rarely have the time to communicate it to their supervisor, much less see the improvement seen through to completion.[17]

Thus, it is key for a system to operate with slack and to empower employees to not only think about process improvement, but to communicate their ideas to make sure that the improvements are heard and implemented where appropriate.

So what comes first? Slack in the system to begin process improvement or process improvement to gain efficiencies, thus gain slack? Within the constraints of our hypothesis statement of operating within a manpower constraint, we see that we must first gain efficiencies to reduce the overall workload to gain slack in the system. At first, as there isn't much time to dedicate to process improvements, the gains will be small. But as every minute of slack is gained, the managers will need to make sure they don't overproduce but rather focus on utilizing this time to gain flexibility through cross training. As cross training gains more efficiency, more slack is gained. Eventually, as enough slack is gained, the company will be able to establish process improvement programs. Once this occurs, enough momentum has been gained and then it is up the leadership to keep the momentum by maintaining slack in the system.

We have quoted Zeynep Ton a lot in this chapter, but she provides ample research around proof that investment in the employees and operating with slack has proven to reduce costs, improve quality, and improve customer satisfaction. We lean on her wisdom to conclude the section with the following quote:

> *How can having too many employees on hand reduce costs? First, by preventing the operational problems that come from understaffing. Second, by allowing employees to be involved in continuous improvement in the form of waste reduction, efficiency and safety improvements, and product and process innovation. By creating time for continuous improvement – and by empowering employees – [Companies] makes it possible for its people to identify problems and suggest improvement opportunities. [Companies] makes sure that employees' ideas are heard and that good ideas are successfully implemented.[17]*

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Chapter 3

3 Current State Variability Analysis

The following chapter examines the variability in the current areas that affect production capacity. A detailed current state analysis will be outlined in the follow-on chapter once we gain an understanding of where the variability exists.

3.1 The Current Bullwhip

The Bullwhip Effect can drastically impose unnecessary work further and further upstream from the customer. The overall distortion of demand information can be summarized and compared by utilizing the Bullwhip Factor (BWF). The BWF is defined as the ratio of the coefficient of variations (CV) of the outgoing orders to the incoming orders. Equation (3-1) shows this relationship below, where μ is the average orders per day and σ is the standard deviations.[9]

$$BWF = \frac{CV_{out}}{CV_{in}} = \frac{\sigma_{out}/\mu_{out}}{\sigma_{in}/\mu_{in}} \tag{3-1}$$

This ratio allows us to see how much the variations are amplified at each stage. If the BWF is 1.0, there is no magnification of the original cause of variation. If the BWF is greater than 1.0, there is an amplification of the variation and the company will need to address the causes of this distortion in order to bring the BWF down as close as they can to 1. Vektek's 2018 CV for units/day for each stage is represented below in Figure 3-1

	Customer's Orders (units/day)	Assembly's Orders (units/day)	MFG Dept's Orders (feet/day)
Average (μ)	645	1,920	337
Stdev (σ)	244	1,150	254
Coefficient of Var. (CV)	0.378	0.598	0.753

Figure 3-1: Coefficient of Variation for each stage

Utilizing the information in Equation (3-1) and Figure 3-1, we can determine the BWF at each stage and the total Vektek BWF. The results are in Figure 3-2.

	Assembly	Manufacturing	Total BWF
BWF	1.58	1.26	1.99

Figure 3-2: BWF for Vektek

The resultant BWF shows us there is a distortion of the customer demand onto MFG and in turn, the distortion continues to be magnified at the next stage. This distortion is graphically represented below. The data has been normalized with mean to equal zero and the amplitude to be the associated z-score. The graphs represent a two month period in 2018. We will analyze the causes of this variation in the rest of this chapter.

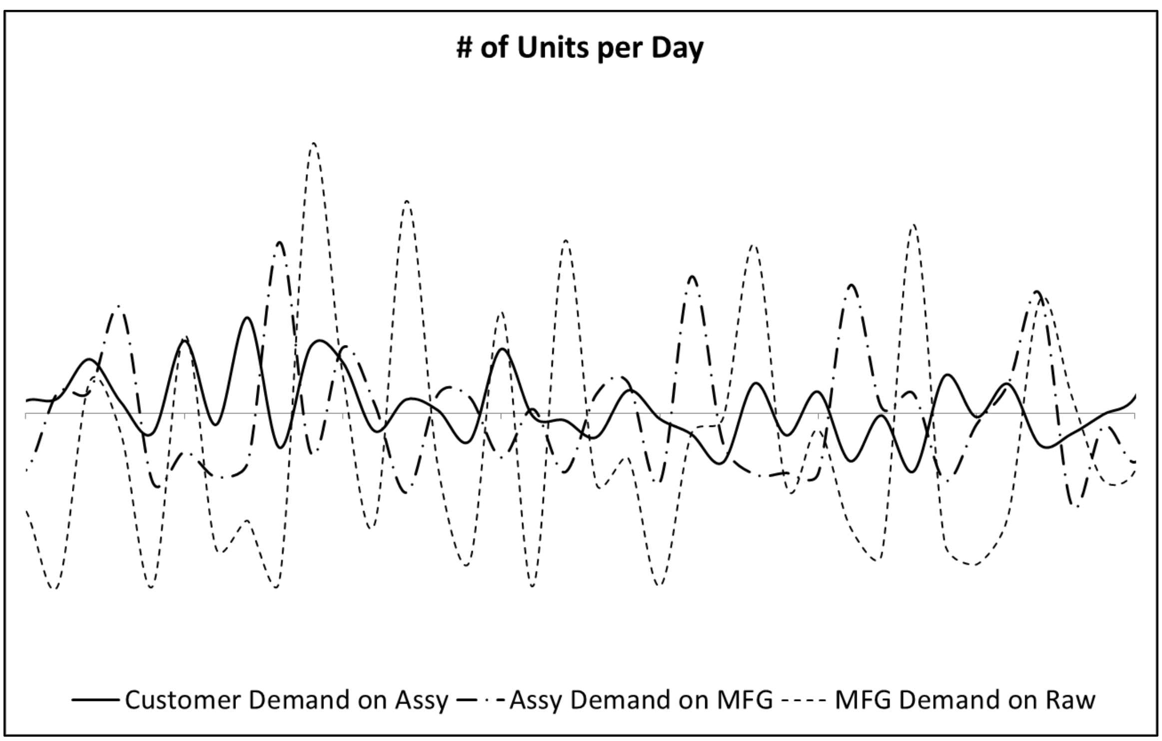

Figure 3-3: Bullwhip of All Demand Levels

3.2 Variable Replenishment Methods

One of the biggest issues surrounding the internal variations of Vektek is the differing replenishment methods within the company. Assembly (Assy) and Manufacturing (MFG) Departments both have set their reorder point to be the value of two month's demand. When the SKU reaches its reorder point, the decision maker makes a judgement call based on experience to determine if the SKU should be reordered or not. Sometimes the SKU will be immediately reordered, sometimes it won't.

The Purchasing Department has set lead times from their vendors to be more than two months for some SKUs. Therefore, Purchasing attempts to set the reorder point based on two months demand but has to inflate it due to their longer lead times. Additionally, Purchasing utilizes safety stock based on an average four week demand. But, just like Assy and MFG, Purchasing utilizes a judgement call to reorder a SKU once it reaches its reorder point. Lastly, there are three decision makers in Purchasing that all have slightly different ordering techniques.

The result is that the three departments, a total of five employees, all have different replenishment methods. As research has shown, having variable replenishment methods can drastically increase the variations. One of the first steps to reduce this variation will be to standardize the replenishment techniques to create synergies between the departments.

3.3 Variable Batch Sizing

Generally speaking, Vektek does not have one piece flow. This means that all SKUs are ordered in batches. In the previous chapter, we saw the negative impact batching has on variation. To further exacerbate this problem, Assy often changes the size of the batch it will order from MFG. An example from 2018; Assy ordered a particular SKU 24 times for an average batch size of 846 with a standard deviation of 637. The resultant variation imposed on MFG is a CV of 0.736. This variation is completely unnecessary and is a result of not having standard replenishment procedures. Reducing the batch size variation will result in a reduction of the BWF in Assembly. Additionally, reducing all the batch sizes will result in a reduction of the BWF for all of Vektek.

3.4 Variable Quality

Currently, there are three established quality gates at Vektek. The first is a quality gate upon receipt of the material from the supplier. After inspection, the material is either put into inventory or returned to the vendor.

The second quality gate occurs at each work station. As the machinist cuts, turns, or mills the unit, a quality inspection occurs. The first unit produced in the setup has 100% of the features inspected. After passing the first unit inspection, only four more units are checked, regardless of batch size. Additionally, the machinists only inspect the critical dimensions of these four units. No SOP exists once a unit fails inspection. With large batches and only inspecting four units, it is clear that when an error occurs, the probability that there is more than one failed unit is very high. Due to these large quantities of failed units, the average batch quality (determined by measuring only the four units) for 2018 was 96.5% with a standard deviation of 6.19%. In Figure 3-4 we see the reported quality of an example SKU to demonstrate the variable quality.

Average Quality: 95.97%

Standard Deviation: 3.8%

Actual Quality on 16 Jobs			
84.0%	93.6%	94.0%	94.1%
95.5%	96.0%	96.4%	97.5%
97.6%	98.0%	98.0%	98.0%
98.4%	98.4%	98.4%	100%

Figure 3-4: Variable Quality

The third quality gate occurs in Assembly. Once the unit has been assembled, a function check occurs in 100% of all units that can be checked. If it fails the function check, a detailed inspection of the unit is conducted. If it is out of tolerance, the Quality Department will inspect the failed dimension of all the units remaining in inventory, removing all the failed units.

Throughout this process, the Quality Department will perform random audits to provide an objective independent examination of the inventory to increase the confidence that all the units produced are within specifications. If the quality gates are properly designed, these audits should very rarely find defects. But in fact, 52% of all defects reported are reported by an audit, machinists report 33%, Assy reports 10%, and the customer reports 5%. This is evidence that the process is not catching the defects at the source which results in conducting a root cause analysis all but impossible.

The variable batch quality and lack of confidence in the overall quality predictably results in increasing the batch size. Decreasing the variability and catching the defect at the source is vital to reducing the overall BWF for the company.

3.5 Variable Manufacturing Machine Setup Times

The impact of long setup times has already been discussed. But to make matters worse, long setup times with high variability makes accurate planning all but impossible. For all the jobs completed in 2018 in MFG, Vektek's average planned setup time was 3.51 hours. But the actual setup time achieved on the jobs averaged 4.81 hours. The longest setup of 2018 was 43.4 hours. The following chart is an example of a SKU manufactured 16 times in 2018. The impact on the variability of the system is readily apparent.

Planned Setup Time: 1 hour

Average Setup Time: 2.12 hours

Standard Deviation Setup Time: 1.29 hours

Actual Set Up Times of all 16 Jobs (hrs)			
0.60	0.67	0.88	1.08
1.12	1.25	1.35	1.55
1.83	2.73	2.80	2.80
3.60	3.68	3.91	5.05

Figure 3-5: Machine Setup Time Variability

For all MFG jobs, the 37.0% time increase from what was planned to what was actually used causes the decision makers to inflate batch sizes.. Due to larger batches, the SKUs are ordered earlier than what is actually needed to ensure that the batch arrives to assembly in time in case the setup time is larger than the planned time.

Increasing batch sizes increases the WIP and lead time, which leads to excessive inventory. In fact, in 2018, Vektek grew the total inventory value by 25.5%. Long and variable lead times will be discussed in the following section.

3.6 Variable Manufacturing Lead Times

The variables that determine the lead time (L) were seen in Equation 2-9. For convenience, the full equation is seen below.

$$L = \sum_{WC} [(Cycle_{WC} * batch) + \ Setup\ Time_{WC}] + \sum_{WIP} [(Cycle_{WIP} * batch) + \ Setup\ Time_{WIP}]$$

From just the equation alone, we see that the variability of the batch size, setup times, and WIP levels will sum to highly variable lead times. But the lead times in manufacturing are not only highly variable, they're also long. The average job waits in queue for six other jobs to be processed before it can be processed. The average lead time in 2018 was 10.8 days with a standard deviation of 11.6 days. The longest lead time of 2018 was 206 days.

Currently, a SKU will be reordered and placed in its appropriate work center queue. Once in the queue, a second analysis will be conducted by the scheduler to determine which job in the queue is needed most. If all the jobs are all equally prioritized, then some machinists will work on the job that has the easiest setup, while others will do first in, first out (FIFO). But no SOP exists to prioritize the work queue. This adds additional unnecessary variability to the system.

Once the job is complete at the work center, the SKU will continue to its next work center where this whole process will repeat. Therefore, setting manufacturing completion dates is all but impossible due to the non-standard replenishment methods, non-standard work queue prioritization, variable WIP levels, and highly variable setup times. Thus, lead time is not used to make planning decisions or to determine inventory levels. Establishing an SOP for work queue prioritization, commonly called production control, and reducing the variations of the factors within the long lead times will result in less variability. The results of these variable factors are seen in an example SKU in Figure 3-6. The details of how the lead time was calculated is seen in Appendix A.

Average Lead Time: 7.6 days

Standard Deviation Lead Time: 6.9 days

Actual Lead Times of all 16 Jobs (days)			
2	2	3	3
4	4	4	4
5	6	6	8
10	14	17	29

Figure 3-6: Variable Lead Time for an example SKU

In Figure 3-6, we see that this SKU was completed in a range of 2 days to 29 days. This is just another factor that has resulted in excessive inventory. Additionally, variable lead times have resulted in a high number of stock outs to be estimated between 10% - 15% of all SKUs stocked out at any given time in 2018. A high number of stock outs and variable lead times make planning difficult which often results in overtime. Overtime analysis will be discussed in the following section.

3.7 No Slack

A highly variable system makes planning difficult and often results in excessive overtime. For our company, the average overtime in 2018 in Assy and MFG was 84 hours and 257 hours per week, respectively. The result is that the company spent an estimated $450k in overtime labor in 2018. The resultant need for overtime and rushing to constantly get work through the system minimizes the slack in the system.

Currently, due to constant rushing of jobs and an inability to properly plan, there is little emphasis on cross training in MFG. Additionally, the added benefits of adding process flexibility is unable to be achieved due to a lack of slack. As stated in the previous chapter, a system works best when there is slack so that there is time for the added benefits of process improvements, quality improvement, and cross training.

Due to the manpower constraints of our system, building slack can only be achieved by reducing the variations of all the factors outlined in this chapter. Additionally, we hypothesize that the stated goal of increasing capacity can be achieved not by adding manpower or new production machines, but rather by reducing the variations of the factors discussed. Reducing these variations will result in reduced WIP, reduced batch sizes, increased quality, reduced overtime costs, reduced lead time, reduced inventory, an increase in customer service, and a more stable system for the employees to enjoy a higher level of job satisfaction. The following chapter will discuss the development and implementation of the solutions to reduce the variability.

Chapter 4

4 Techniques of Data Analysis and Solutions

With an understanding of the current state of our highly constrained system and of the background information that leads to variability, the following chapter shows an analysis and proposed solution(s) to reducing the variability in each area in order to increase production capacity.

4.1 Bullwhip Analysis and Roadmap

Within our system, there are many areas we need to focus on in order to reduce the variability and determining where to start can be overwhelming. But, the Bullwhip provides a roadmap for areas to focus on first.[14] Using Figure 4-1, we see that we have three distinct areas to focus on: Assembly, Manufacturing, or Raw Material.

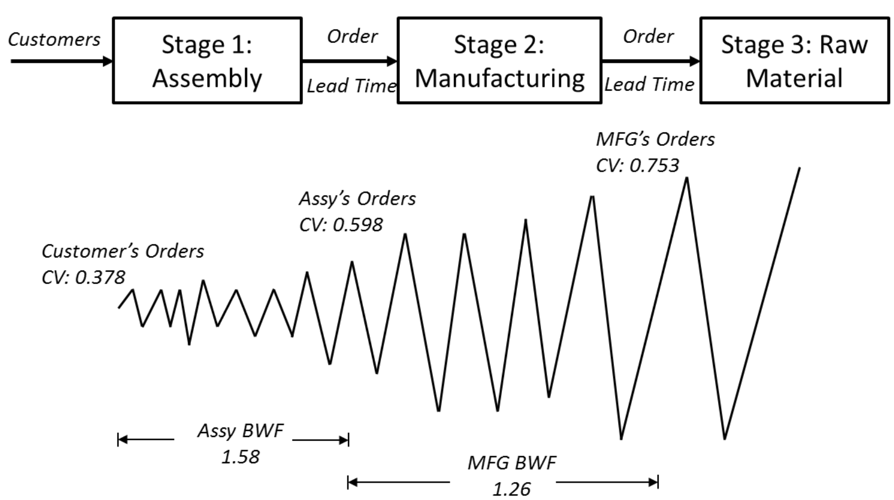

Figure 4-1: Bullwhip Map of Vektek

Reducing the variability in stage 1, Assembly, will have a dampening effect across the entire system. Reducing the variability in stage 2, Manufacturing, will have a dampening effect in stage 2 and 3, but will have no positive effect on stage 1. Therefore, to have the biggest impact on increasing the production capacity of Vektek, we need to start as close to original source of variation that is possible, the customer. Thus, the roadmap becomes clear that we should reduce the variations in Assembly before Manufacturing.

4.2 Assembly Processes Analysis and Improvements

There are three main sources of variation within Assembly: batch sizing, replenishment methods, and inaccurate forecasting.

4.2.1 Batch Sizing

In the analysis section, we saw that there was no SOP for batch sizing, which results in highly variable order quantities imposed on MFG. A simple solution to reduce the variability is to set the batch sizes to a fixed quantity. This would quickly reduce the order variations felt on MFG. Once proposed to the Assembly Manager, he quickly realized the impact of standardizing the batches ordered and immediately established the policy to not change the batch size.

Additionally, the Assembly's management philosophy is based on the mass production philosophy to have larger batches to reduce total workload while increasing utilization. But upon gaining a better understanding of the impact of batch size reduction, the manager quickly changed philosophies to reduce batches. He reduced the batches on all 647 SKUs that are currently forecasted. With this reduction, we should expect to see less variability in the workflow and less WIP. Additionally, we should expect the Finished Good Inventory (FGI) levels to be reduced.

4.2.2 Replenishment Methods

The next area to address is the variable replenishment techniques between departments. The proposed solution to establish a replenishment method in Assy needs to be repeatable in the MFG and Purchasing Departments. Currently, the reorder point is based off the total demand for two months. For the SKUs that can be made quickly, it is economically reasonable to keep less on hand than the SKUs that takes longer to make. So strategically, this increases the cost of inventory as some SKUs can be made in a very short period while others take longer.

Utilizing the Periodic Review Policy provided by Graves and Willems [19], we can use a formula that will remove bias and opinions, provide a repeatable solution for all the departments, and give us statistical confidence to be able to meet a desirable customer service level. Specifically, Equation 2-1, 2-2, and 2-3 establish the inventory levels based on lead time, demand, and batch size. The only modifiable variable is the predetermined customer service level. This solution provides a benchmark to aim for while still allowing the human experience and expertise to slightly modify the service level based off business decisions such as desired service level or total cost of inventory.

Utilizing the Periodic Review Policy allows strategic decision makers to easily understand the capital investment required to meet a desired customer service level. This also provides clarity for decisions makers to understand how to achieve operational goals. For example: if the goal is to lower the cost of inventory while maintaining the same service level, the only variables the operations team can control to reduce inventory is lead time and batch size. Therefore, the team can direct their efforts into lead time reduction or batch size reduction in order to achieve the desired outcome.

Categorizing and segmenting the finished goods inventory (FGI) for Assy is vital to understand where to start implementing the Periodic Review Policy. Stable SKUs rarely have outliers that could skew the learning required to gain confidence in the model. Therefore, in order to implement the new replenishment SOP and to gain confidence in the science, it is reasonable to convert the most stable SKUs first. For Vektek, the category of SKUs is seen in the first column in Figure 4-2. We see that currently, there are 647 forecasted SKUs and 1,399 SKUs that are not forecasted.[2] Vektek keeps SKUs at FGI if they sell on average of 10 units a month, regardless of number of orders.

[2] Not Forecasted means that there is no inventory for the SKU in FGI

	Current	Periodic Review Policy	Sell 1, Make 1 Policy	No Change
Highly Stable SKUs (CV < 0.33)	61	61		
Stable SKUs (0.33<CV<0.5)	127	127		
Forecasted Unstable SKUs (0.5<CV)	459	459		
Non-Forecasted SKUs	1,399		167	1,232
Total FGI SKU	2,046	647	167	1,232

Figure 4-2: FGI SKUs

Once aware of the scientific benefits of the Periodic Review Policy, the decision makers began to slowly convert the existing reorder points to the new modeled inputs. After converting the 20 most stable finished goods SKUs, the managers closely watched and learned to see how the assembly and Material Requirement Panning (MRP) systems responded. One week later, 41 more SKUs were converted. For three weeks, the managers closely monitored the systems. After gaining confidence in the new methodology, the managers quickly implemented the remaining 459 forecasted unstable SKUs.

4.2.3 Inaccurate Forecasting

The question now becomes, can we achieve an added benefit of converting some non-forecasted SKUs into forecasted SKUs? For any company whose competitive advantage is product speed to the customer, the more FGI SKUs they forecast, the more available product they can quickly ship. Forecasting SKUs reduces the likelihood of missed sales or late shipments which increases their competitive advantage of high customer service level. Additionally, Graves and Willems [19] provide an explanation that strategically placing safety stock can decouple the downstream operations from the upstream operations. For a company that has long and variable manufacturing lead times, this decoupling effect is vital to achieve the competitive advantage. [3]

So which SKUs can we project and how much should we keep? Figure 4-3 provides a histogram for the units per order for an example SKU which can be used to set the inventory levels to increase customer service level for a minimal cost.

4-2.

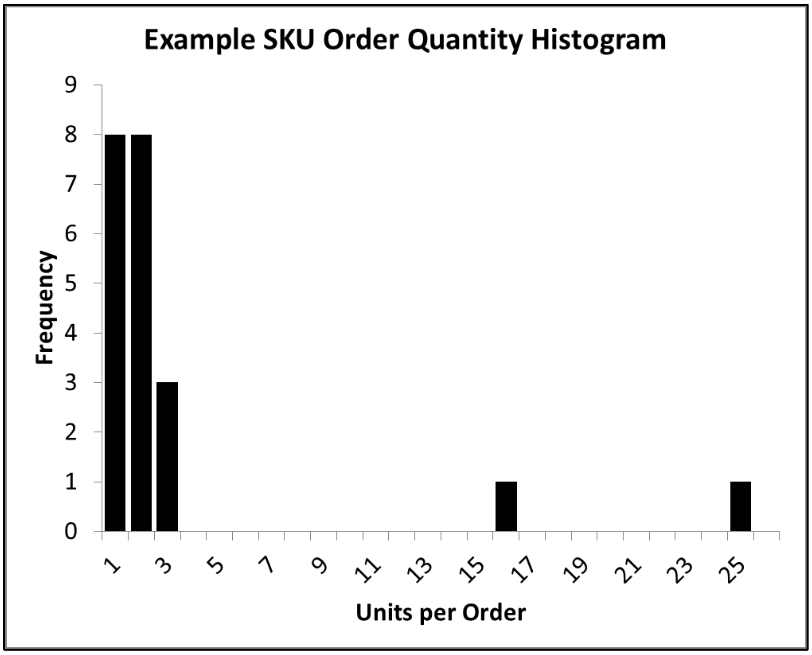

Figure 4-3: Example SKU for Sell 1, Make 1

The histogram shows us that the SKU was ordered 21 times in 2018. The average order quantity was 3.52 units per order. Currently, due to these outliers and small order quantity for the lowest 19 orders, this SKU is not projected. Desiring to maintain the competitive advantage, we want to now project as many SKUs as possible. But if we were to utilize the Periodic Review Policy to determine the inventory levels, we would keep an average of 15 units in FGI. Clearly, this is too costly to satisfy just the outliers. Removing the outliers, the Periodic Review Policy will tell us to keep an average of 4 units in FGI. This is much more realistic, but still doesn't quite optimize our FGI. As you can see, keeping 4 units in FGI is still too high as the probability that two orders totaling four or more units on the same day is minimal.

An alternative solution is to only keep three units in FGI. This will result in an immediate fulfillment of 90.5% of all orders while minimizing the cost of inventory. When a sell of three units or below occurs, the company will be able to immediately fulfill the order. Then, Assy can replace the size of the order when there is spare capacity the following days instead of rushing to achieve their competitive advantage, product speed to the customer.

With this new strategy, Sell 1 Make 1, in mind, Vektek made an $87k investment in more inventory to achieve their competitive advantage by projecting 167 more SKUs, seen in Figure 4-2.

4.3 Manufacturing Process and Solutions

There are four main sources of variations within Manufacturing: replenishment methods, quality, machine setups, and production control.

4.3.1 Replenishment Methods

We recall from the previous section that the inventory reorder point for MFG is based on the total two month demand and that we desire to create synergies between the departments by repeating the same replenishment method in order to reduce the BWF. While adopting the Periodic Review Policy, the Assembly Department chose to slowly convert a few SKUs at a time. This implementation method is logical as the batches are small and the lead time is between 1 – 2 days for all SKUs. Meaning, any necessary recalibrating only needed to be conducted on a few SKUs and any mistake or refinement can be recovered from in a couple of days.

But as we have seen in MFG, the lead time is vastly longer and the batches are larger. Thus, there is a greater need to ensure the Periodic Review Policy is finely tuned before introducing the new inventory levels as recovering from any mistakes would take weeks, if not months. Therefore, it is necessary to model the system to run simulations to gain confidence before the changes go live in the MRP system.

4.3.2 Developing the Simulation Model

Utilizing the data from 2018, such as batch quality, reorder points, sales, and lead times, we can accurately model and repeat what occurred. Once the model is correct, we will simulate what MFG Operations could have looked like if the safety levels and reorder points were based on the Periodic Review Policy. Then, after the simulation is complete, we can compare the simulation results to the actual results to see if the Periodic Review Policy requires more calibration. The end goal is to gain confidence that the new inventory safety stocks and reorder points will provide the decision makers with more reasonable inventory levels.

The model developed in excel uses the actual inventory level on January 1, 2018 for every SKU. The actual demand is applied to the inventory on hand the day that it was used. At Vektek, as units are consumed throughout the day, MRP tracks the usages in real time. But if a SKU's inventory on hand reaches or goes below the reorder point, the scheduler is not alerted until the next day. This is because the MRP system is set up to only alert the company after all the day's operations are complete. For example, if a SKU drops below its reorder point on a Monday, the scheduler will be notified first thing Tuesday morning and he or she will create a job to reorder the SKU. Therefore, the model is programmed to reorder the predetermined batch the day after it drops below the reorder point.

Additionally, quality is accounted for in the model by taking the actual quality and applying it to the batch ordered. Meaning, if the quality was 95% in 2018 and the model reordered a batch of 200 units, only 190 units would arrive after a specific period for that SKU. The time period from reordering to arrival is the average lead time of the particular SKU in 2018. Once at the end of the lead time, the batch replenishes the total quantity on hand. During the replenishment period, if demand on the part continues to reduce the inventory on hand below zero, the inventory becomes negative the appropriate amount. This is exactly what happens in our current system at Vektek and is commonly called a stock out.

With the model programmed, we can simulate every day of the year to see daily outputs such as total daily workload, total inventory dollars, and number of stock outs. Additionally, we can change the z-score for our safety stock to see the impact on all the above categories to determine the appropriate capital the company needs to invest to keep the customer service level it desires to have. Further details on the data generation can been seen in Appendix A.

4.3.3 MFG Actual vs. Simulation

The model results are seen in Figure 4-4. The Actual column shows what was conducted in 2018. The Model column shows the results of the program with the current reorder points. The Simulation column shows the results of what the year would have looked like if the reorder points were derived from the Periodic Review Policy. After careful evaluation, the manager settled on a desired service level of 89% for the simulation.

	Actual	Model	Simulation
Total 2018 Jobs	2,927 jobs	2,957 jobs	2,769 jobs
Daily Stock Outs	47.9 SKUs	42.1 SKUs	15.1SKUs
Total Workload	142,464 hrs	145,040 hrs	137,275 hrs
Daily WIP Avg	\$335,096	\$352,447	\$340,833
End of Year Inventory	128,433 units	144,116 units	117,994 units
EOY Inventory Value	\$1.77mil	\$2.19mil	\$1.83mil

Figure 4-4: MFG Simulation Results

As you can see, the model recreated the actual results accurately. The two main differences that can't be simulated was the human decision making for reprioritizing the queues at each work center and delaying the jobs after the MRP has suggested the company reorder a SKU. This is likely the main difference in inventory value at the end of the year. This is further discussed in Appendix A.

To summarize the results, we see that with the simulation, there would have been 3.6% less workload, but with a 68.5% reduction in stock outs. Additionally, we would have ended the year with less total inventory but with a higher inventory value. This shows that establishing our inventory levels on statistics allows us to do more with less. Meaning, the previous customer service level of 96.2% with 128k units on hand would have risen to 98.8% with 8% less inventory.

With the model and simulation complete, the operations team has gained the confidence and understanding that basing the inventory levels on statistics is not only viable, but preferable to the current technique. With this knowledge and confidence in the model, the team decided to input all the new safety stock and reorder points into the MRP at once.

4.4 Quality Variability Analysis and Solution

The quality gate at the work center appears to be insufficient as more bad units are caught by the auditor than the machinists.[3] 76.1% of the 2,927 jobs conducted in 2018 reported bad quality on at least one unit during the job. The average number of bad units reported was 4.40 units per job with a standard deviation of 11.2 units per job. This confirms our suspicion that when a bad unit is found that the likelihood that there is more than one in the batch. In fact, the worst quality job was a reported 107 bad units out of 120 total units. Perhaps, the defect would have been caught earlier if more units were inspected.

The evidence is overwhelming that the inspection gate needs to change. We simply don't know what is happening between the inspections. All we know is that the auditor is catching more of the bad units instead of the machinist. Operating under the assumption that the machinists are reporting all the bad units and that they do not pass along known bad units, then we can assume that the bad units are made in between the inspected units. For example, when working on a batch of 1,000 units, the machinists will produce 250 units between inspections.

[3] We define a bad unit as a unit that is inspected and is out of the specified tolerance

This leaves ample room for error or for the machine to drift out of tolerance and then back into tolerance before the machinists inspects a unit.

The first and immediate step should be to increase the sampling size for the machinist. In doing this, the data can be gathered to gain insight about what is happening between the current inspections. The AQL Standards seen in Figure 4-5 is recommended as the first starting point.

Batch Size	Sample
2	2
9	5
16	6
26	8
51	13
91	20
151	32
281	50
501	80
1201	125

Figure 4-5: AQL Sampling Size[18]

As data is collected, the standard 6-Sigma AQL chart should be followed to determine if the sampling size should go up or down. During this process, creating standard work cannot be over emphasized. Much like how the *andon* system at Toyota creates standard processes to find the bad units and to conduct root cause analysis, SOPs need to be developed to ensure that not only are the bad units caught, but that the processes can be fixed to prevent future bad units.[10] Until the sampling sizes are set appropriately for each batch size and machine type, SOPs are implemented, and root cause analyses are conducted, we should expect the total reported unit quality of 98.2% will not improve and the quality variability will remain high.

4.5 Machine Setup Process Analysis and Improvements

In 2018, Vektek conducted 3,994 machine setups for a total of 14,262 setup hours. This resulted in the average setup taking 3.57 hours. As previously noted, actual machine setup times for Vektek in 2018 were higher than the planned setup times. To understand why the times are so long and to see how we can reduce the times, a machine setup time study is vital. Figure 4-6 shows the results of the time study done on a single machine with a highly qualified employee. The planned setup time for this job was 4.5 hours.

	Time per Category (min:sec)	Percentage of Total Time
External Setup	21:17	13.6%
Internal Setup	104:53	67.0%
Wasted Time	30:14	19.4%
Total	2 hours 36 mins	

Figure 4-6: Setup Time Study

Because there is no established setup SOP, this worker conducts the external setups during the dedicated setup time instead of doing the steps before and/or after the dedicated setup timeAdditionally, the wasted time[4] was spent on needless tasks such as walking to gather inspection equipment and searching for tools and equipment.

It is clear from the figure that establishing an SOP derived from the SMED process outlined by Shigeo Shingo will reduce the setup time by at least 13.6%. Additionally, the wasted time, such as sorting through the clutter to find the proper tools, can be mitigated by conducting 5S at the work station. This additional 19.4% would result in a 33% reduction in total setup times. The result would reduce the 2 hour and 36 minute setup time to 1 hour and 45 minutes. Two more similar studies were conducted on different machines with different employees with the percentages seen in Figure 4-7.

	Study 2	Study 3
External Setup	5.69%	6.59%
Internal Setup	57.4%	60.2%
Wasted Time	36.9%	33.2%

Figure 4-7: Two Additional Setup Time Studies

These two workers for study 2 and 3 had already conducted the external setup steps before the official setup time begun, just like SMED recommends. Their natural understanding of how to separate external setup steps from the internal setup steps shows the benefit as their external setups only accounted for approximately 6% of the total setup time. But, they both had high percentages of wasted time due to searching for tools, troubleshooting CNC programming, and walking to ask for help.

[4] Wasted time is defined in Lean as actions such as waiting, defects, and motion

From these three specific time studies, it is clear that conducting 5S at each workstation will have a huge benefit in setup time reduction. Establishing an SOP and following Step 1 of SMED will have an additional benefit of conducting the external setup steps before the setup time begins. From these two simple steps, we can safely assume that there would be an immediate 20% – 30% reduction on all set ups. This could drastically allow the batch sizes to be reduced. Batch size analysis and reduction will be discussed in the next section.

4.6 Batch Size Analysis and Reduction Method

Yuan and Graves remind us that increasing batch sizes increases the production variability.[4] Therefore, our stated goal of reducing the variations means that we should strive to reduce the batch sizes. Reducing the batch sizes has the added benefit of reducing both the lead time for the job but also for all the jobs in the work queue. However, reducing the batches will increase the annual workload on the work centers. Therefore, it is important that when reducing the batches that we do not exceed the capacity of the manufacturing system.

The regular machine hours, total machine hours minus overtime hours, for 2018 were 75,849 hours. The current forecasted demand on MFG is 69,503 hours. Therefore, we can comfortably add 3,000 hours to the machine shop by decreasing the batch size, which still leaves 5% capacity if demand shifts up.

There are many ways we can chose to reduce the batch sizes. For one, we can just reduce every single batch by a certain percentage. This is a simple method that can be easily implemented. But will it help us achieve our goal of reducing the variability of the system? The short answer is yes and no. Yes, it will reduce our variability because we're reducing all the batch sizes. No, because although we are reducing all the batches, those SKUs that have abnormally long processing times will still be outliers that cause variability due to their unproportionally long times. In Figure 4-8, we see the current processing times histogram.

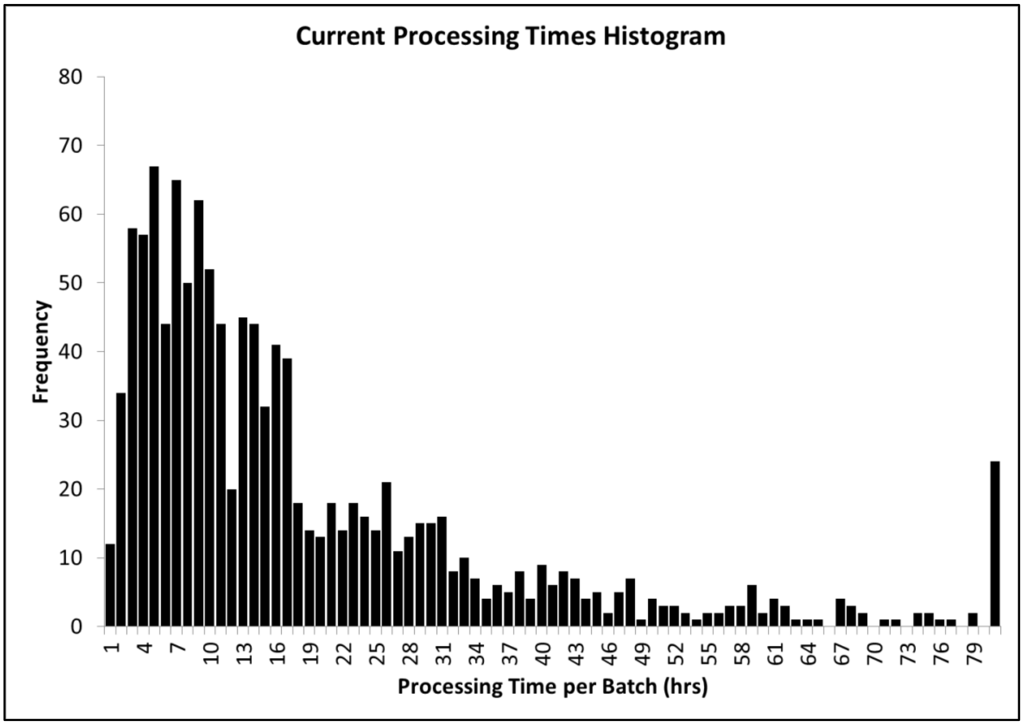

Figure 4-8: Current Processing Times Histogram

The method of reducing everything by a percentage may not be optimal due to the jobs that have unusually long setup times. Recall that decreasing the batch size increases the annual jobs. So ideally, we would only want to increase the annual jobs that have short setup times and decrease the annual jobs that have long setups. Additionally, the median is 12 hours while the mean is 19 hours. We see the very long right tail distribution will vastly slow down the majority of the SKUs and causes high arrival variability. This is commonly known as the 80/20 Principle or Pareto's Principle. The Principle states that the minority of causes, inputs, or efforts usually lead to a majority of the results, outputs, or rewards. For our system, we see that the 20% largest processing times will impact 80% of the remaining SKUs. Therefore, we can adjust just 20% of the SKUs and impact 80% of the system. [8]

Therefore, an alternate reduction method is to analyze the setup time to processing time ratios. With this method, we want to reduce the highest ratios more than the ones with the smallest ratio. For example, SKU A has a setup time of 1 hour and processing time of 49 hours while SKU B has a setup time of 4.5 hours and processing time of 110 hours. We want to reduce both, but it would be more beneficial to reduce SKU A by a larger percentage than SKU B due to SKU A's smaller setup time. This way, we can reduce the outliers by a higher percentage, and we can actually move the mean closer to the median. Using this approach, we find the optimal strategy is to reduce 23.7% of the SKUs by an average of 38%. The comparison of the two methods is seen in Figure 4-9.

	Even Reduction	Ratio Reduction
Batch Reduction	22%	38%
SKUs reduced	100%	23.7%
Inventory Value Reduced	$261k	$274k
Avg Lead Time Reduced	16.2%	17.1%

Figure 4-9: Batch Reduction comparison

From the results, we see that reducing the batches based on the ratio is superior in every category. Additionally, utilizing the ratio reduction, we can reduce more variability as well. The new adjusted processing times are seen in Figure 4-10. The median is still 12 hours but the mean has changed from 19 hours to 14 hours. Comparing the histograms, we see that the long processing times have been all but eliminated and there is less variability between jobs.

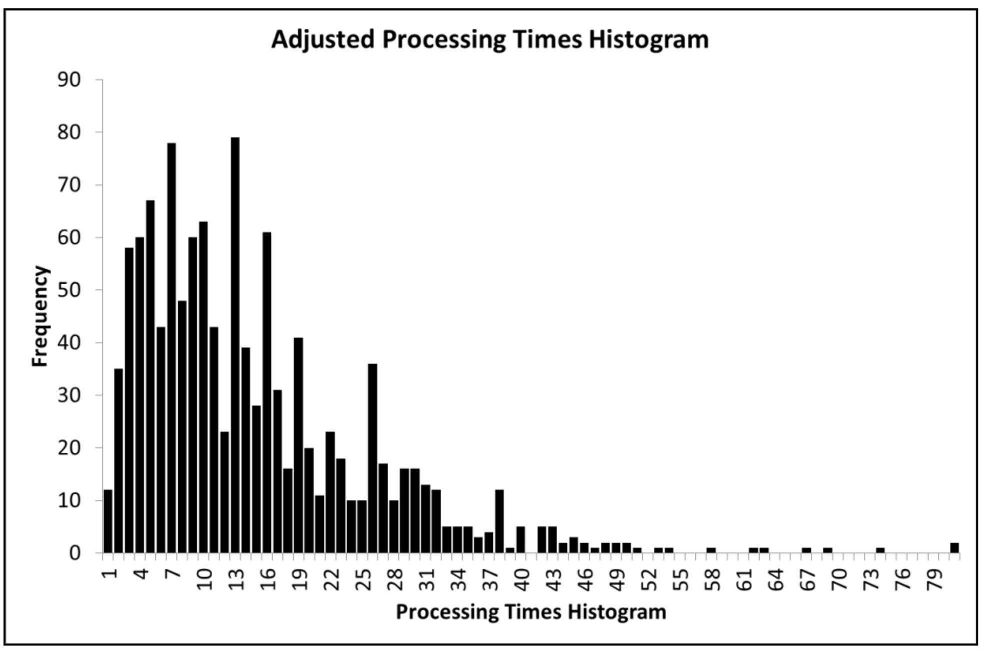

Figure 4-10: Adjusted Processing Times Histogram

Reducing the batch sizes has an added benefit of reducing the overall lead times. Lead time analysis will be discussed in the following section.

4.7 Lead Time and WIP Analysis

Recall from Chapter 3, the variables that are easily within our control that determine the actual lead times: WIP at the work center, setup times, and batch sizes. For convenience, the lead time formula is below.

$$L = \sum_{WC}[(Cycle_{WC} * batch) + \ Setup\ Time_{WC}] + \sum_{WIP}[(Cycle_{WIP} * batch) + \ Setup\ Time_{WIP}]$$

With a better understanding of the high variability of these factors, we are not surprised to learn that lead time has the highest variability of all factors studied. The only way to reduce both the length and the variability of lead time is by reducing the factors that determine the lead time. But a closer examination into WIP variability is necessary to complete our discussion on lead time reduction.

Karamarkar explained in his research that, "Larger lead times lead directly to proportionally larger WIP inventory. Safety stocks are adversely affected in two ways. First, they must protect against longer lead times. Second, the variability of forecasts is greater as the horizon becomes longer. Thus, safety stocks can be expected to grow more than proportionally with lead times."[7] Therefore, we see that the longer the lead time, the more WIP. But the more WIP, the longer the lead time. This cycle of doom will continue to spiral out of control unless something is done.

Therefore, if we control one, we can control the other. Graves [4] points out that it is inherently easier to control WIP and measure lead time instead of controlling lead time and measuring WIP. WIP at our company accounts for the queue time the jobs must wait on before it can be processed. Karamarkar explains that "it is a common characteristic of multiproduct batch manufacturing that [SKUs] spend most of their time waiting in queues rather than actually being processed."[7] Our company fits this explanation perfectly. The average batch sits in queue and waits for six other jobs to be completed before it can be processed. The setup to processing to queue ratio for the company is 1:5:33. This means that for every 5 hours of processing, the job waits 33 hours. The details of how this was derived is seen in Appendix A.

Since the average job waits for six other jobs to be completed, controlling the WIP and reducing it will have a huge benefit on the lead time reduction. Reducing WIP can be done in a multitude of ways. The first is simply controlling jobs released to the manufacturing floor.

Another method is utilizing the popular *Kanban* or *CONWIP* systems. Both limit queue capacity and prevent overproduction.[15]

Another way to reduce WIP is in setup and batch reduction. As the average job waits in queue for six setups and six batches to be processed, it still must wait for its own setup before work can begin. Because of this, any process improvement in setup time reduction will be felt seven times. Additionally, each individual unit waits for all the other units in the batch to be processed before it can move on to the next job. Therefore, batch reduction reduces the queue time even more and can drastically reduce the WIP and lead times. The last method to control WIP is managing the queue prioritization. This analysis will be conducted in the following section.

4.8 Production Control

The current WIP in a work center queue is only prioritized by hot[5] and normal jobs. Currently, normal jobs at the queue are equally prioritized, regardless of how long it has been in queue or when the WIP is expected to be completed. As we saw in the lead time section, determining the actual completion date is very difficult due to the variations that exist that make up the actual throughput time.

Graves[4] provides insight and evidence that production control in a job shop is often very difficult and cannot and should not be very sophisticated for it to work properly. He states that, "Production control is often based on a queue management system. Production control, in its crudest form, merely prioritizes the jobs in queue at each work center, typically by means of some measure of the perceived urgency of the jobs." One objective of production control is to minimize the variability between the planned lead time and the actual throughput time.[3]

With that in mind, for the system to further reduce the variability, a proper SOP for production control needs to be implemented. Utilizing the research from Graves, the company needs to establish a work queue based off the perceived urgency of the jobs. With no dates set and long production lead times, we must use the inventory on hand to determine the urgency. If a stocked-out SKU is the most urgent, then the least urgent would be a SKU that has just reached

[5] A hot job is a job that is needed for a customer order, the component inventory is stocked out, or the scheduler manually establishes it.

its reorder point (ROP). Since every SKU's ROP is different, we can show the relationship of urgency as a ratio. This relationship and categorization is seen in Figure 4-11.

	$\frac{On\ Hand}{ROP}$
Hot Job	Less than 0
Very Urgent	0.00 – 0.25
Urgent	0.26 – 0.50
Normal	0.51 – 0.75
Low	0.76 – 1.00
Very Low	1.00 +

Figure 4-11: Production Control Categorization

As a SKU is reordered, it will likely be in the 'Low' category. When it reaches a work center queue, the machinist will simply work on the highest priority job first. Intuitively, the machinists understand that although the job is needed, there is still some inventory on hand to meet customer demand. As customer demand reduces the ratio, the SKU will naturally drift up the priority list. This way, the queue can automatically rearrange itself based on need instead of a desired throughput time.

An added benefit is for the manpower manager. With this method, he or she can properly balance the manpower workload based off priority instead of work center queue length. For example, Work Center A may have 10 jobs in the queue and Work Center B has three jobs. Currently, Work Center A will be prioritized over the Work Center B. This is because the manager has no clarity on what is needed most and only works on keeping all the jobs at the work centers balanced. But what if Work Center B has one Very Urgent and two Urgent jobs while Work Center A has three Normal and seven Low jobs? With this proposed standardized production control, the manager can now make a properly informed decision and staff Work Center B before Work Center A because of the higher priority jobs. The benefits of establishing standard work cannot be over emphasized. Creating this SOP will drastically reduce stock outs and provide much needed clarity and guidance for the workforce.

4.9 Cross Training

Zeynep Ton reminds us that cross trained employees are more productive, have better job satisfaction, reduce production variability, and reduce the overall costs.[17] We intuitively understand that the more cross trained employees we have in our departments, the more flexible we can be to meet the changing demand. But a fully cross trained workforce takes time to develop and is highly unlikely. Recall that we have a roadmap of how to achieve the benefits of a fully flexible workforce in a minimal amount of time through the concept of *links* and *chains*. A *link* connects one person to one skill. A series of connecting *links* forms a *chain*. Through research, Graves has been able to prove that the biggest benefits of chaining occur when there is one single, closed loop chain in the system.

4.9.1 Assy Cross training

The Assembly Department has had a big emphasis on cross training over the past few years, and the benefits are obvious. The employees work as a team, appear to have high job satisfaction, are more productive, and are capable to surge to meet an increase in demand when needed. In fact, the first shift in Assembly has achieved a full 2-skill closed loop chain. This chain is seen in Figure 4-12.

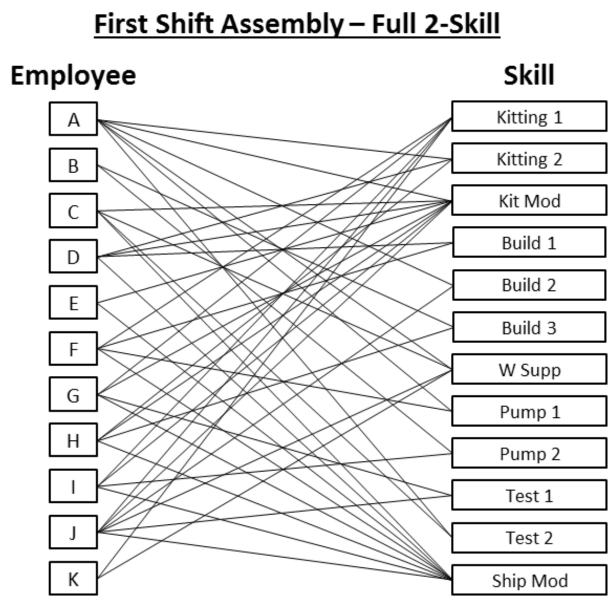

Figure 4-12: First Shift 2-Skill Chain

We notice in Figure 4-12 that there are more skills required than employees. The result is that some employees have more than 2 skills. Second shift, however, has only seven employees for 12 skills. Therefore, almost all the employees will need four skills. We see in Figure 4-13 on the left that second shift has 20 *links* and will require four additional *links* to close the loop. The proposed additional *links* are seen on the right. Once these four skills are acquired, Assembly will have a full 2-skill department and will achieve essentially the same benefits of a fully flexible work force.

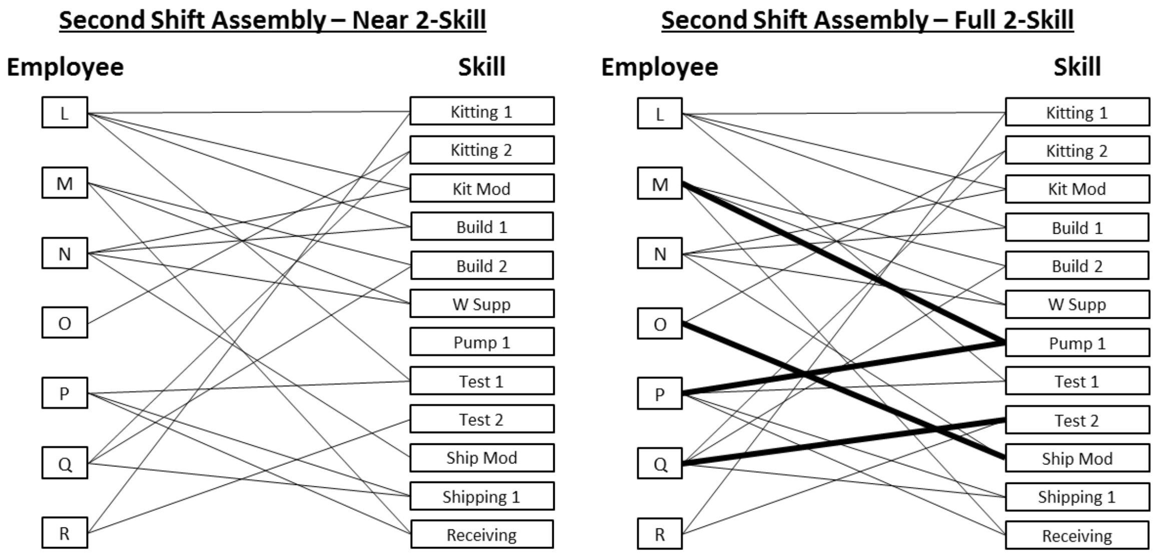

Figure 4-13: Second Shift Near 2-Skill and Proposed Full 2-Skill

4.9.2 MFG Cross training

Manufacturing, just like Assembly, will greatly benefit from having a single closed chain. But, Manufacturing's number of skills is more complex than Assembly. Therefore, deciding where to add flexibility can be difficult to discern. Utilizing the same mapping technique as before, we can quickly decide where we will receive the most benefits. In Figure 4-14, we see the current skill map on the left. Only nine links will need to be added to close the loop and to create one long chain. The proposed skills to add are on the right. Acquiring the skills is the first step to creating a flexible workforce. After gaining the appropriate skills, it is now up to the leadership to properly manage the skills to keep the workload balanced.

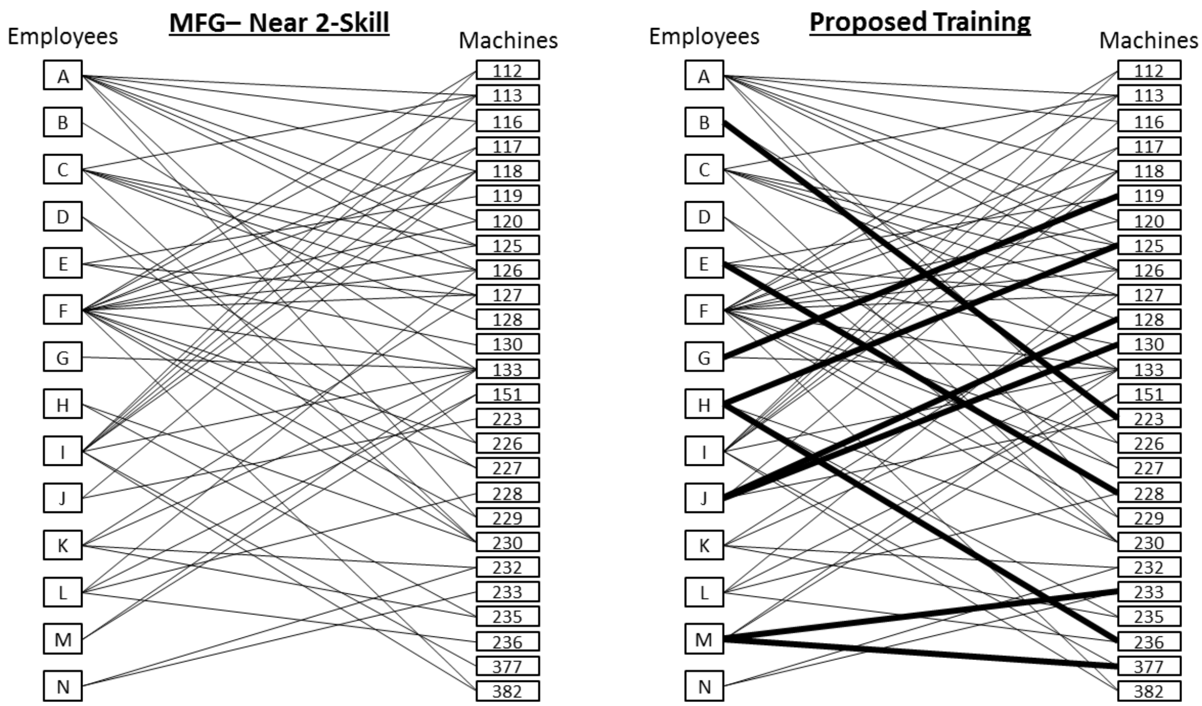

Figure 4-14: Manufacturing Cross Training

As you might have noticed, there are twice as many machines as workers. Therefore, although these proposed changes will give MFG flexibility, half of the machines will be without an employee dedicated to them. Deciding where to dedicate labor becomes even more important. But, utilizing the production control recommendations from the previous sections, the MFG leadership will be able to decide where to dedicate workers. Adding this flexibility and managing it properly will not only increase the throughput, but it will reduce the variations of the throughput.

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Chapter 5

5 Results and Discussion

Many of the solutions proposed in the preceding chapter have been implemented throughout a six month time frame. Due to the time gap in between many of the process improvements, we can isolate the results and directly tie them to the process improvement implemented.

5.1 Assembly Results

In the following sections, there will be a series of charts showing before and after improvements. Any columns that are striped will reflect an assembly change (appear to be grey). There will always be two as the improvements were implemented over a five week period. MFG improvements will be reflected with a black polka dotted pattern. Due to changes implemented over a single day, these charts will only have one column.

5.1.1 Bullwhip Factor Reduction

Recall from Figure 3-2 that the BWF for Assembly was 1.58. After the BWF analysis and proposed solutions were conducted, Assembly proactively implemented the following solutions:

- The batch size of all 647 forecasted SKUs were reduced by an average of 24.6%.
- Standardized batch sizing to not change between made-to-stock orders
- Implemented Reordering points based on 2018 data into safety stock and min
- Forecasted 167 SKUs with the Sell 1, Make 1 methodology

With Assembly reducing the variations in batch sizing, inaccurate forecasting, and daily operations, we should expect the overall BWF for Assy to drop. The results are undeniably positive. The BWF dropped from 1.58 to 1.43 with a 26.5% reduction in the variation. Figure 5-1 shows the before and after results of the BWF.

	2018			After Assy Improvements		
	Avg	Stdev	CV	Avg	Stdev	CV
Customer Demand (units/day)	645	244	0.378	579	176	0.305
Assy Demand (units/day)	1,920	1,150	0.598	1,470	643	0.436
BWF	1.58			1.43		

Figure 5-1: Bullwhip Factor Results

5.1.2 Overtime Reduction

As we've learned, the variations of the system make planning difficult. So as these variations are reduced, we should be able to plan better. Better planning will reduce costs as less overtime will be required. The 17 weeks prior to the first improvement (first grey column), Assembly averaged 84.0 overtime hours per week. We see in Figure 5-2 that as the variations begin to be reduced due to the process improvements, the overtime hours began to drop. The last official changes were made five weeks after the first changes (second grey column). As we see two weeks later, overtime has been all but eliminated.

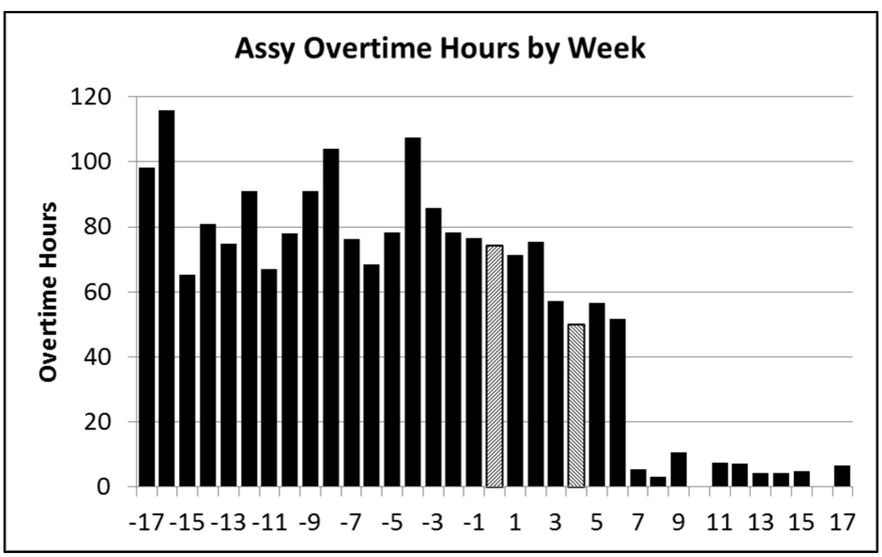

Figure 5-2: Assy Overtime Hours

5.1.3 On Time Shipments

Remember that the company's competitive advantage is its speed to deliver the customer's orders. Therefore, the 15 weeks prior to the change, the company had an impressive on time shipment average of 97.89%. But the standard deviation was 1.03%. Since the process improvements, the company has improved the on-time shipment to an average of 98.74% and also reduced the standard deviation to 0.45%. This is a 40% reduction in late shipments and a 56% reduction in the standard deviation. The results are graphed below in Figure 5-3. The triangle data points are before the improvements, the diamonds are the transition period, and the squares are the after improvements. Zero on the x-axis represents the week the first change took place.

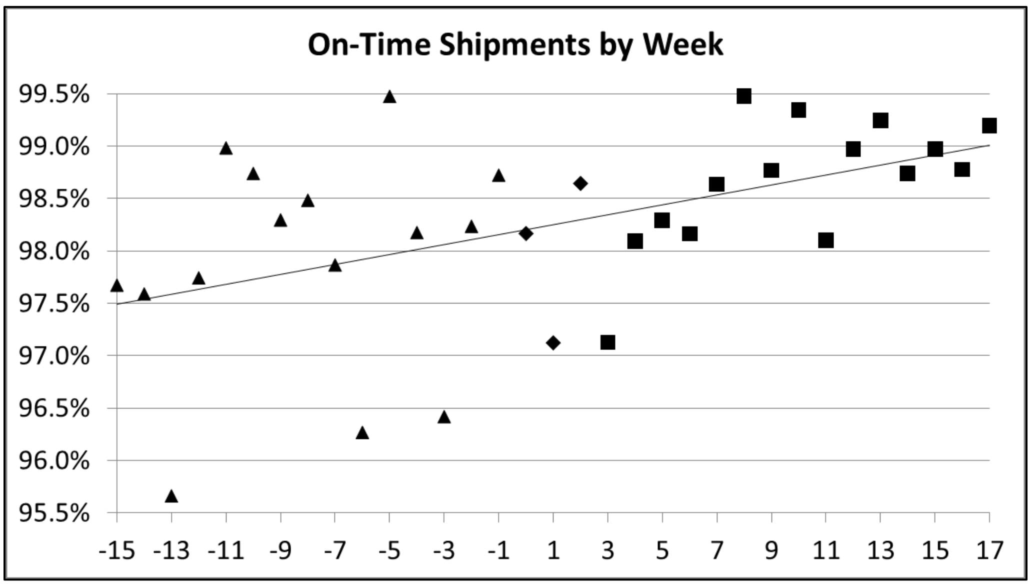

Figure 5-3: On-Time Shipments

An additional metric to measure the success is with respect to the on-time shipments relative to early shipments. The company will ship the product early if they: a) have the SKU on hand and b) the customer allows it. Therefore, any improvement in the early shipments shows that the right inventory is on hand at the right time. We see evidence in Figure 5-4 that the forecast is now more accurate than it was before. Before, the average was 39% of all shipments were early. Now, the average is 47% and appears to continue to rise. Also, as expected, the variability has been reduced by 32.2%.

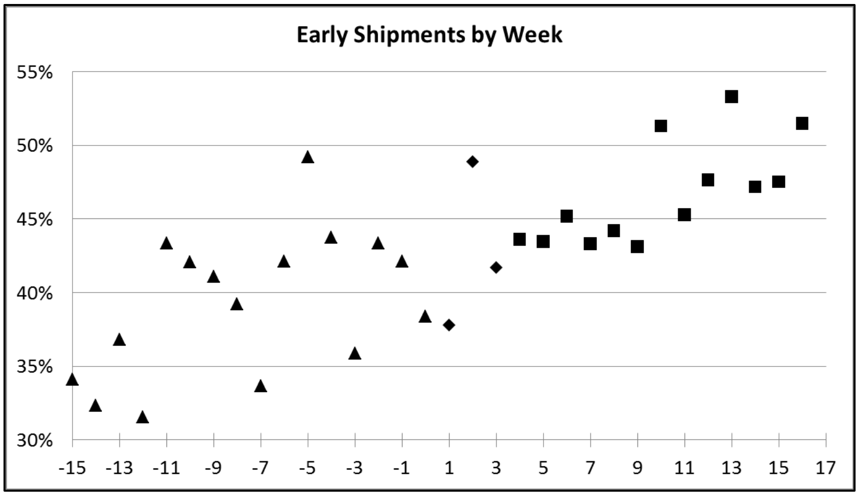

Figure 5-4: Early Shipments

5.1.4 Workflow and WIP Reductions

As the batch sizes are reduced, we should expect the WIP to not only be reduced, but for the lead time to be shortened. Unfortunately, we are unable to accurately measure the lead time in assembly, but we have observed that the work is getting through the shop faster than before. Fortunately, we can verify that the WIP has been reduced. Before the batch reductions and implementation of new reordering methods, the 15 week WIP value average was $338k. After the final change, the average has been $155k, a 54.1% reduction. The weekly WIP averages are seen in Figure 5-5. Again, week zero represents the beginning of the improvements while the last grey column represents the last week of the improvements.

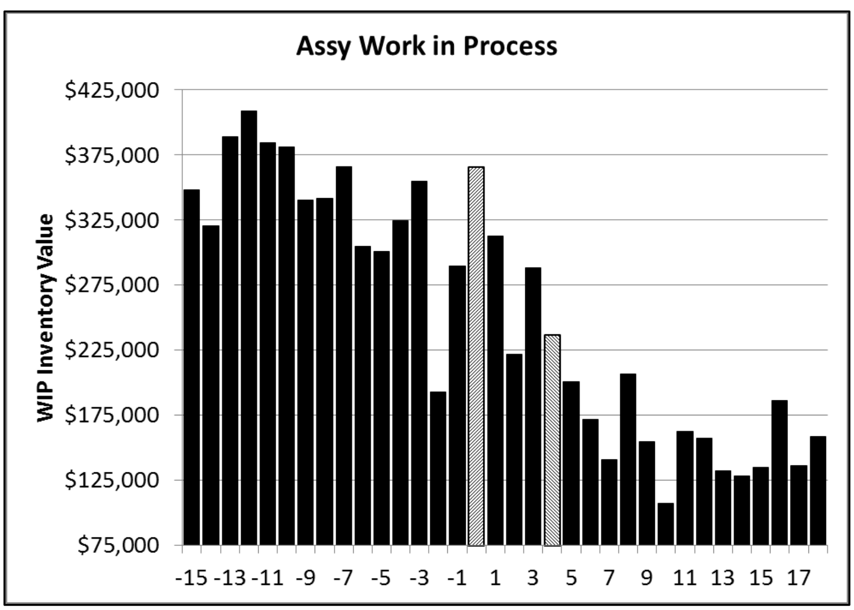

Figure 5-5: Assy WIP Reductions

In addition to the objective results of WIP reduction, another observation needs to be recognized. Before implementing the Sell 1, Make 1 policy for the 167 SKUs, when a customer ordered one of the 167 non-forecasted SKUs, the Assembly team had to rush the order through the shop while disrupting the regular flow of material. In the past 12 months, there was an average of 4.82 orders per day that would disrupt the operations to achieve the competitive advantage. But with this new inventory policy, the company can now ship approximately 90% of those orders without having to make any new inventory. After the order is filled, the team simply replaces the inventory but without the need to rush the order. Therefore, it can easily flow through the assembly line which prevents needless overtime or expediting.

If you'll recall, since the improvements, the on-time shipments increased while the early shipments also increased. Additionally, the overtime hours have been all but eliminated. Also, WIP and lead time have been reduced while customer service has increased. To summarize the results, Assembly is now able to get more product to the customer faster while working less and keeping less inventory because the variations have been reduced to allow steady state operations.

5.2 Manufacturing Results

Manufacturing operations is subjective to the demand variations downstream, Assembly. Therefore, they are at the mercy of Assembly's operations. Any inefficiency in Assembly will be felt in Manufacturing. Therefore, as process improvements occur in assembly, not only will we see a benefit in Assembly, but we'll see an additional benefit upstream in Manufacturing. So, over the course of implementing the solutions to reduce the variations, we will see two types of improvements; Assembly improvements that affect Manufacturing operations, and Manufacturing improvements that directly impact operations.

5.2.1 Reduced Required Workload

Recall that the variations of Assembly will require more demand upstream on Manufacturing than what is truly necessary to meet customer's demand. This is summarized as the Bullwhip Effect. Therefore, any reduction in Assembly variation will reduce the required workload imposed on Manufacturing.

The required workload is defined as the required workload, in terms of unit of labor, required to replace a unit that is consumed by Assy. For instance, if a MFG SKU of batch size 60 has a setup time of 60 minutes and a processing time of 3 minutes per part, then when Assy consumes one part, they are essentially removing 4 minutes of work from the component inventory. Therefore, MFG will need to spend 4 minutes of labor to replace the unit.

In the three months leading up to Assembly's process improvements, the demand imposed on it required 1,680 hours of work per week. But after all the process improvements were made in Assembly, the required workload reduced by 30.8% to 1,162 hours of work per week. In other words, Manufacturing now has 30.8% more capacity than what is required. The week by week hours of required work is seen in Figure 5-6.

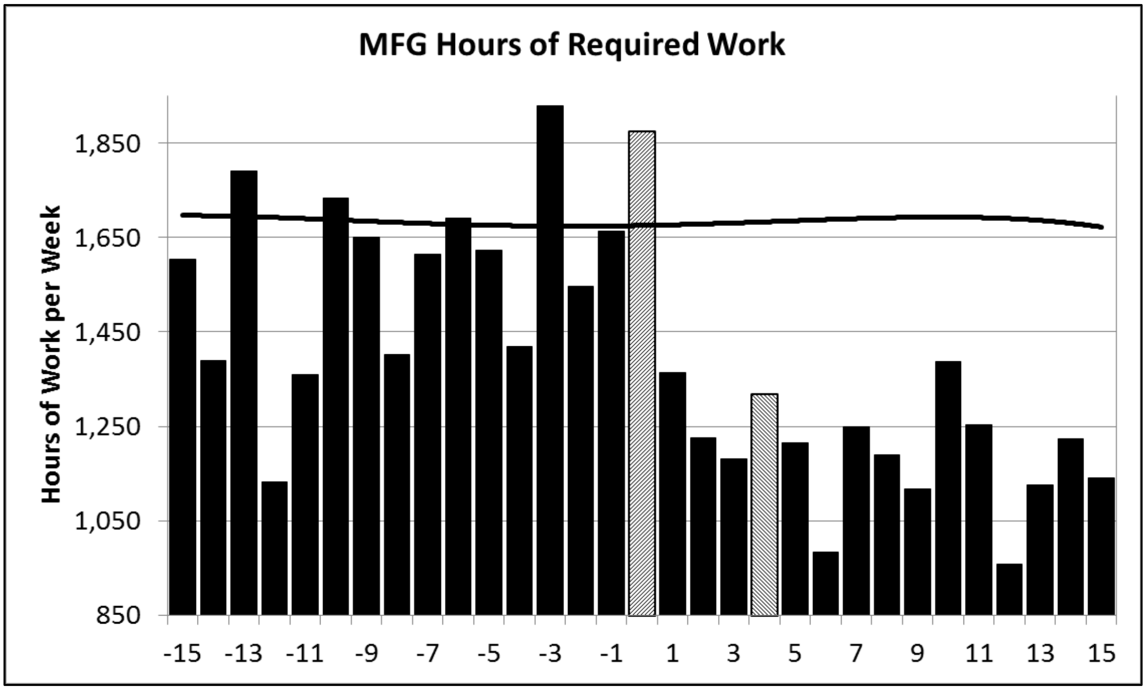

Figure 5-6: Required Workload for MFG per week

In Figure 5-6, we observe that the MFG hours of required work that Assembly imposed onto MFG drastically dropped after the improvements. The solid black line on the graph is the trend line for the sales data during this period.[6] The trend line shows us that the sales were steady during this period and had a slight rise after the Assy improvements. Therefore, since the sales were steady both before and after the changes, we can positively conclude that the improvements in Assy are responsible for the reduction in MFG hours of required work.

[6] The actual sales data has been removed to protect the company's sensitive information. This line shows the change in Goods Sold from week to week. The flat line shows that from week to week, the change was minimal and even had some growth in the later weeks.

5.2.2 Work In Process Reduction due to Assembly Improvements

As we observed in the previous section, the reduction in Assembly's demand on MFG greatly reduced the workload required on MFG. This in turn, should reduce the WIP (number of jobs) in MFG. The 30.8% reduction in required workload had a corresponding 36.8% reduction in jobs in MFG. Before the improvements, the 15 week average was 326 jobs per week. After the changes, the average reduced to 208 jobs per week. Figure 5-7 shows that the required workload vastly reduced the WIP.

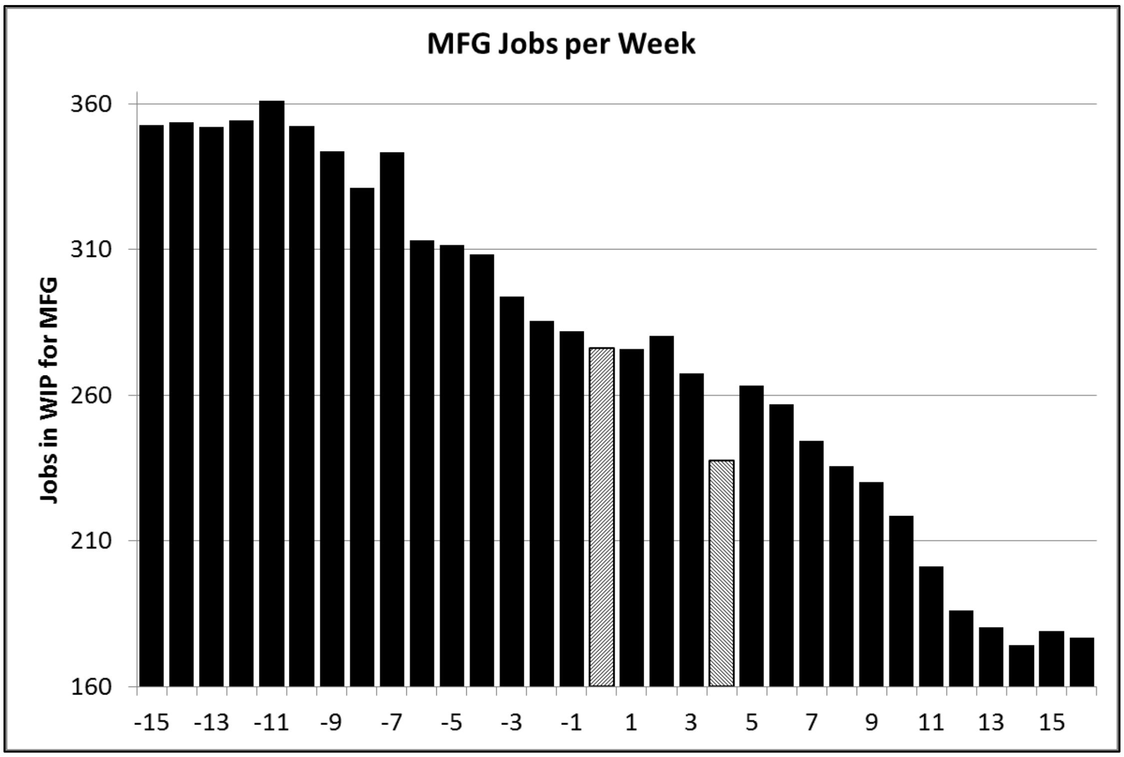

Figure 5-7: MFG Jobs Per Week Reduction

5.2.3 Work In Process Reduction from Manufacturing Improvements

As we have observed, MFG was able to gain capacity due to Assembly's reduction in variability. To gain further capacity, Manufacturing implemented the following improvements:

- Implemented Reordering points based on statistics of safety stock and min
- Standardized batch sizing to not change between made-to-stock orders
- The batch size of 227 SKUs were reduced by 38%

Implementing the Periodic Review Policy for replenishment, we would expect that some SKUs' reorder point would be increased above the current on hand inventory. Thus, when it was implemented all at once, the number of jobs in WIP should increase. But, as time progresses, our model showed us that the total number of jobs on the floor will decrease as the reorder points are now based on statistics and lead time instead of a flat rate of two months' demand.

Both events occurred, just as modeled. Overnight, 25 additional jobs were put into WIP. But as time progressed, the system responded exactly how we anticipated. The average 15 day average before the change was 242 jobs in WIP per day. One and a half months later, the daily average has dropped to 175 jobs in WIP, a 27.7% reduction. The daily results are seen in Figure 5-8. Additionally, it took about a month, or 21 manufacturing days, to reach a new steady state. The polka dotted column represents the day of the new replenishment method.

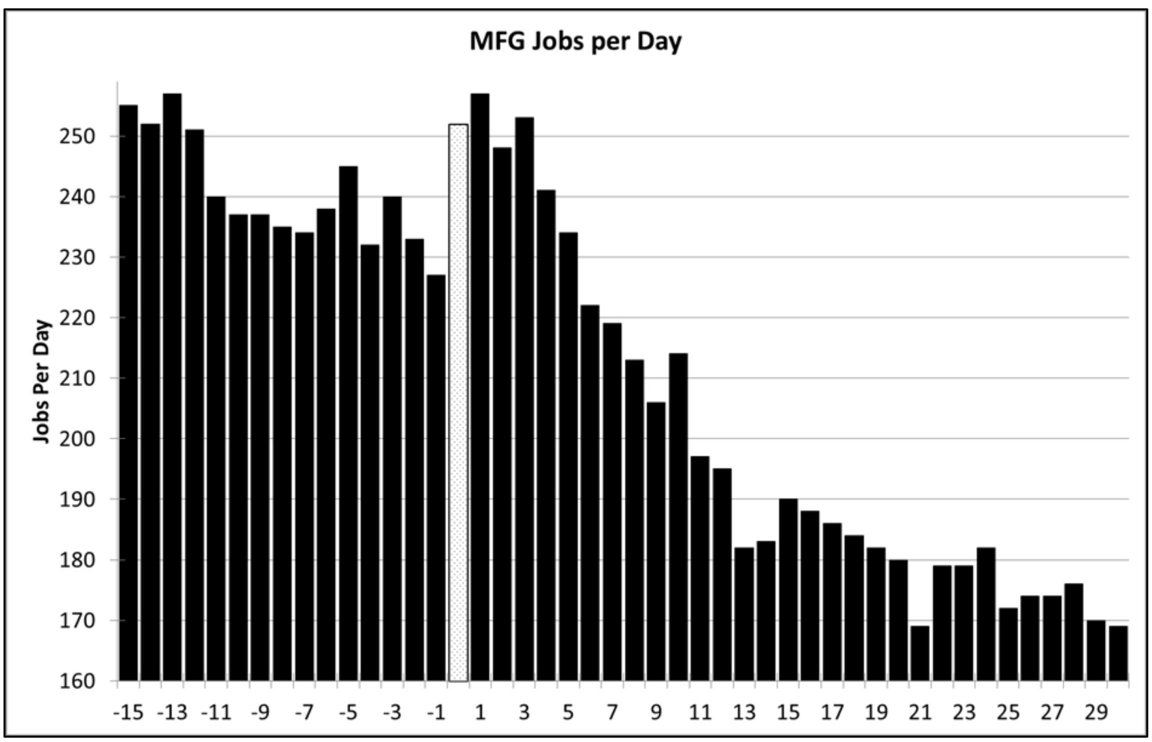

Figure 5-8: MFG Jobs per Day

Combining the reduction in WIP due to Assy improvements along with the reduction of WIP with MFG improvements, we have a total of 46.6% reduction in MFG WIP jobs. But, because the product mix is always changing in a job shop, the value of the inventory in WIP will also be changing. Therefore, in addition to observing the jobs reduction, we should also observe the WIP inventory value reduction. The 15 week average of MFG WIP value before the first Assembly improvement averaged $319k of WIP per week. Following the last MFG improvement, the average reduced to $252k of WIP per week, a 21.0% reduction. This is graphically represented in Figure 5-9, where the first and last Assy changes are in grey and the MFG change is in white.

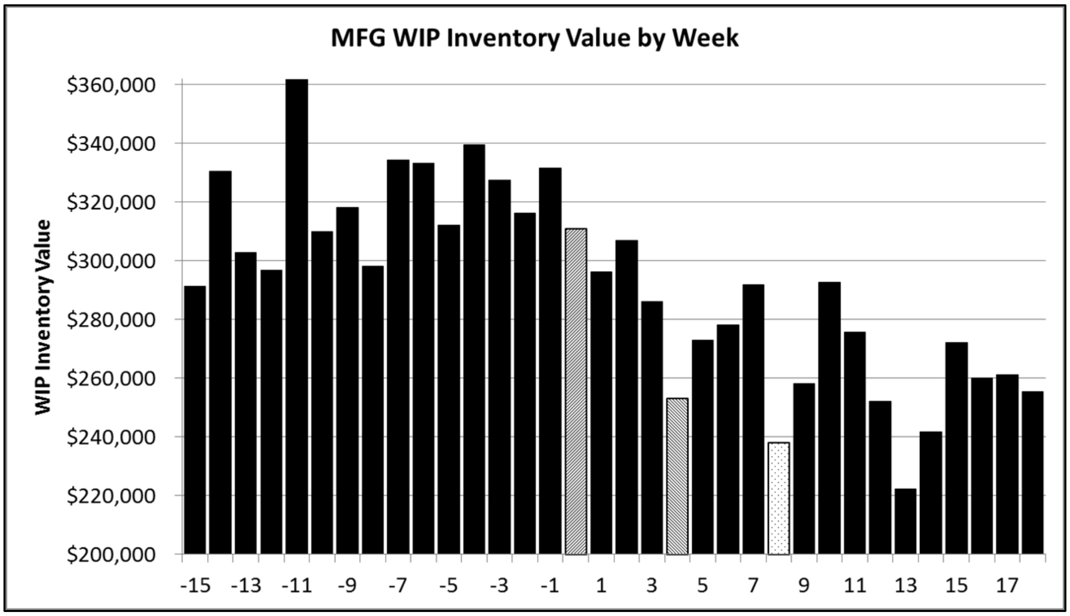

Figure 5-9: Weekly WIP Inventory Value

5.2.4 Service Level

As the daily WIP reduced, the jobs were able to get through the manufacturing department quicker. Arriving quicker than before, we should expect that the SKU service level for component inventory to increase. Additionally, reordering the SKUs based off lead time should have an added benefit of an increase in service level. Recall that the MFG model developed predicted that utilizing the Periodic Review Policy will increase the service level while reducing the WIP. The average service level before the changes was 89.0%. Since the number of jobs in WIP reached stead state (day 21), the service level has averaged 91.2%, a 20% decrease in stock outs.

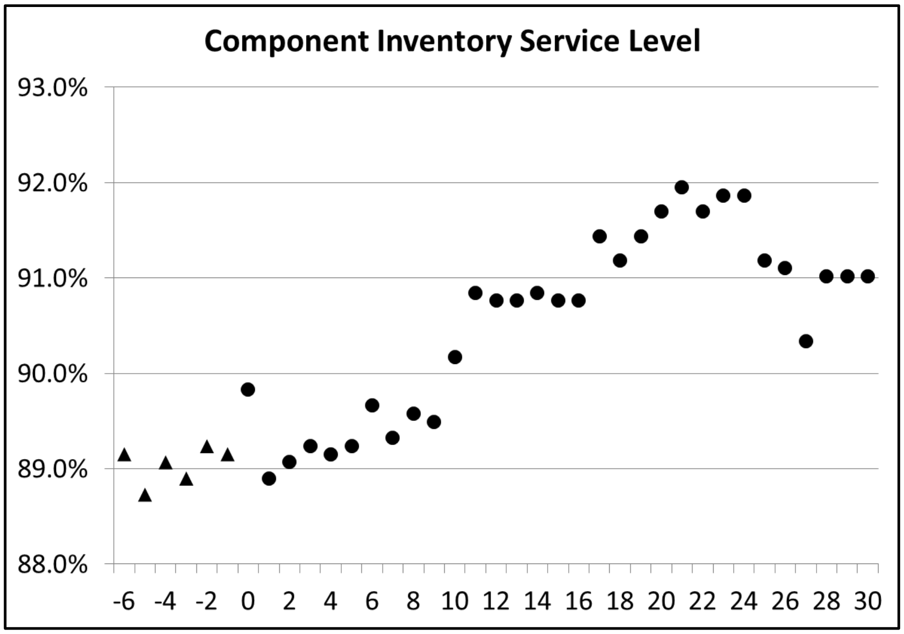

Figure 5-10: Component Inventory Service Level

5.2.5 Overtime Reduction

Prior to any improvements made within this research, the overtime per week for Manufacturing was all but mandatory for all employees in Manufacturing. In fact, Manufacturing averaged 202 overtime hours per week the 20 weeks before the first change. With reduced workload required due to Assembly improvements and MFG improvements, the overtime was steadily reducing until eventually it was no longer required. This progression is seen in Figure 5-11.

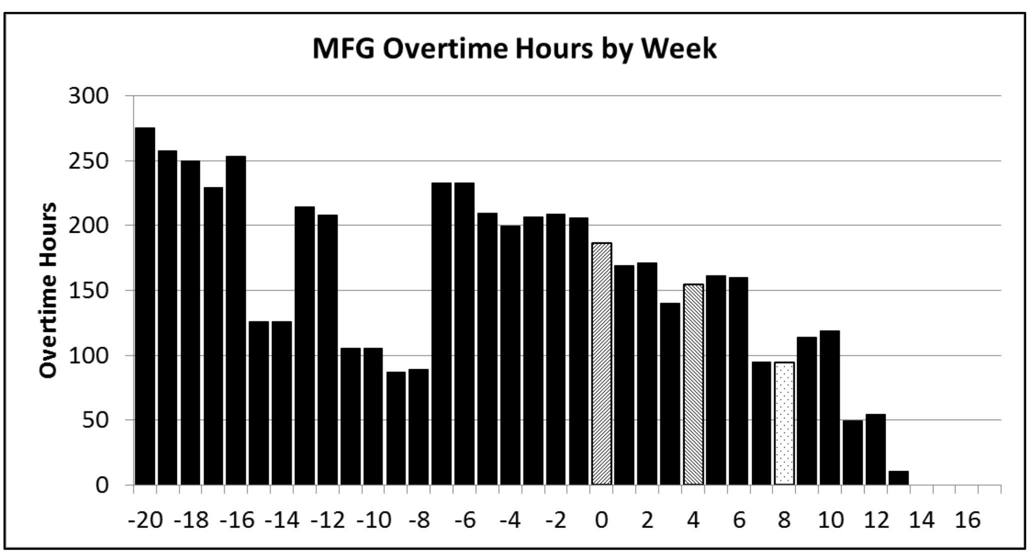

Figure 5-11: MFG Overtime Hours by Week

5.3 Overall Results and Capacity Gained

The overall results are clear. By reducing the variations, 26.5% in Assy alone, we were able to improve all three pillars of operations: costs, lead time, and service level.
We were able to reduce the costs of:

- Assy WIP Inventory Value reduced by 54.1%, a $183k savings
- MFG WIP Inventory Value reduced by 21.0%, a $67k savings
- Assy Finished Goods Inventory by 2.33%, a $37k savings
- MFG Component by 3.30%, a $69k savings
- Assy Overtime Costs by 95%, an estimated $176k annual savings
- MFG Overtime Costs by 100%, an estimated $456k annual savings

The lead time:

- Assy lead time was reduced by approximately 50%
- MFG lead time was estimated to be reduced between 15% and 24%

The company improved customer service:

- Late Shipments were decreased by 40%
- Early Shipments increased by 20.5%
- Number of stock outs for MFG was reduced by 20.0%.

If you recall, the 15 weeks prior to Assembly's changes, MFG worked 1,517 regular machine hours (total hours minus overtime hours) per week to keep up with Assembly's demand. After the 26.5% reduction in variation in Assembly, Manufacturing only must work 1,162 hours per week to match Assembly's demand, a 76.6% reduction. Therefore, Assembly demand can grow another 23.4% before MFG reaches its capacity. Therefore, we can conclude the reduction in required manpower and required work for the machines by reducing the variations supports our hypothesis that you can gain capacity by reducing the variations.

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Chapter 6

6 Conclusions

The findings in this research should not be ignored. The highly constrained company was able to gain capacity with minimal capital investment. But the work has only begun for our system. The following section will discuss next steps and then we will conclude with a note for companies that are in similar situations.

6.1 Recommended Next Steps

6.1.1 Process Flexibility

‘Flexibility is the ability to respond to change without increasing operational costs with little or no delay in response time’ – David Simchi-Levi.[14] Flexible operations have proven to reduce risk, increase speed, reduce total production cost, improve responsiveness to demand, and increase service level.

Simchi-Levi spends considerable amount of time in his book, *Operations Rules*, discussing the benefits of process flexibility. In his research, he developed a chart that we have shown in Figure 6-1. This chart shows the strategy that should be utilized with a system of given characteristics. Currently, Assy is operating in both quadrant C and A while MFG is operating in quadrant B and D. But given the unique characteristics of each department, perhaps each department should adopt a new strategy. The benefits of this topic should be further researched and implemented to further reduce the variability.[14]

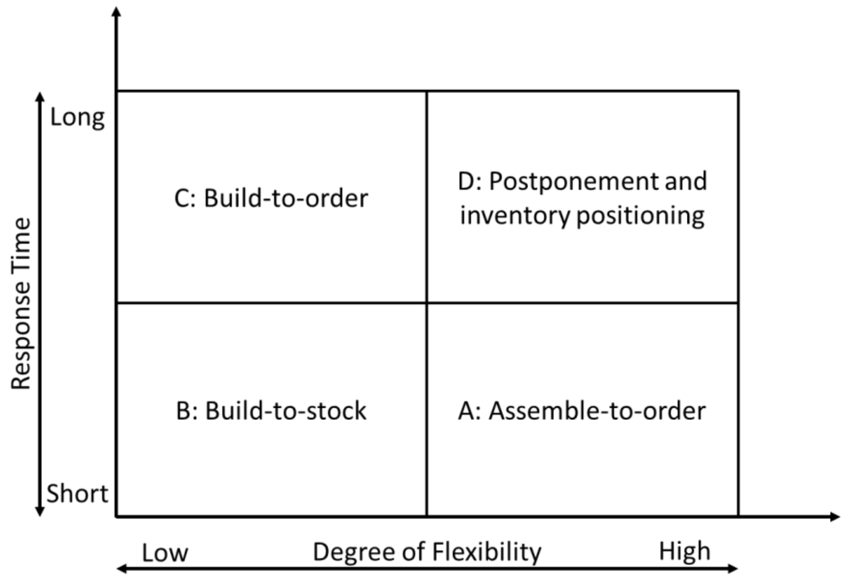

Figure 6-1: Flexibility and the Manufacturing Strategy

In Chapter 2, we discussed process flexibility. For our system, many of the SKUs manufactured have only one pathway in which they can be made. Since the company is essentially a job shop, the product mix is always changing. Thus, the bottleneck might change from day to day. Therefore, when a job is released to the floor and there is a current bottleneck along its operational path, the company has little it can do to divert the product to a different path to avoid the bottleneck.[3]

Due to this issue, considerable time and effort should be applied to increasing the agility of the machine shop. This task will be a big undertaking due to the numerous factors that have to be considered as not all machines will be able to make all the products due to tooling, machine type, size of material, etc. But once all the factors are categorized and considered, we have no doubt the company will be able to follow the techniques outlined to achieve a single closed loop chain.

6.1.2 Quality Improvement Program

Quality has been discussed throughout this research. But without proper data, we are unable to make any definitive conclusions as to the solutions to the quality issue. Due to this, the recommendations in this paper are designed to develop the data to assist with root cause analysis.

The next steps should be focused not only on fixing the issues but streamlining the quality process. Currently, the inspection records are all but impossible to consolidate for data analysis since everything is hand written. Therefore, a monetary investment would be required to digitize the inspection process to allow for a streamlined analysis. On top of this benefit, there would be an opportunity to synchronize the engineering drawings, CNC programs, and inspection records together. This would allow for immediate feedback from one to the other while minimizing wasted time for the machinists working with three different documents.

6.1.3 Push vs. Pull

A push versus pull system is a widely researched topic and should be considered for one of the next areas of research for our company. As a preview for what could be gained, Simchi-Levi provides a simple chart for determining what the strategy should be for a given system. Figure 6-2 shows the chart where Lead time is on the x-axis and Demand Uncertainty is on the y-axis.[14]

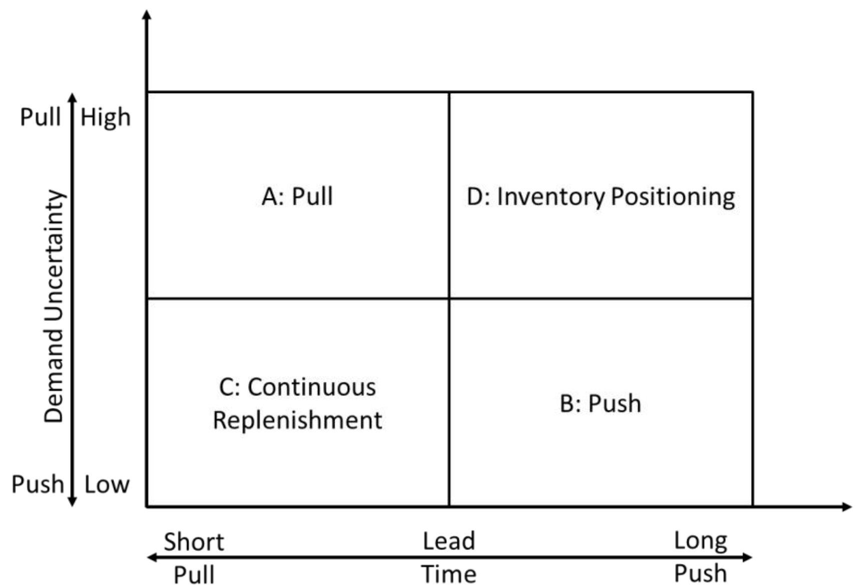

Figure 6-2: Push vs. Pull Chart

Utilizing the chart for our system, we see that Assembly should be operating in quadrant A or C for all their SKUs. But currently, Assembly has segmented the SKUs into quadrants A and B. MFG is in its correct quadrant in quadrant B. Therefore, due to the different characteristics of each department, different strategies should be implemented. Establishing a push-pull boundary and the benefits of establishing a pure pull system for Assembly warrants further research for Vektek.[16]

6.1.4 Continuous Education Program

Variability is often the result of a lack of education or information sharing. Therefore, to further reduce variability, a continuous education program should be implemented where everyone is educated on the benefits of such topics like 5S and Setup Reductions. Education also helps provide a more satisfying job experience and enables cross training to propagate throughout the company. Lastly, continuous education has proven to increase quality of companies' products and processes. The benefits of education should not be under emphasized and should be implemented at its earliest possible moment.

6.1.5 Process Improvement Program

Zeynep Ton said, "People closest to a problem have the best chance of spotting it and what causes it. They are also the most motivated to solve it because it's causing them pain every day."[17] Art Byrne also emphasizes that the employees need to be empowered to improve the system. Both researchers provide ample evidence that operationally excellent companies are ones that have a process improvement department that solely focuses on soliciting feedback and implementing the improvements throughout the company. Byrne's research shows that only when a company dedicates manpower to a process improvement department will the company ever actually begin the continuous improvement journey.[1]

Process improvement within our systems should first focus on 5S and SMED. As mentioned, 5S is a continuous program that has many benefits from creating standard work to minimizing frustration on the job.[6] Additionally, once the foundation is built, SMED should be pursued at all costs. Through the research, we kept going back to the negative effects of long and variable setup times. SMED is a process that will greatly reduce these variations while also shortening them.

The benefits of process improvement programs reducing the variability should be further researched to determine where Vektek should implement it.

6.2 General Implications for Similar Firms

The research findings and solutions implemented are not unique to our company, only the specific details are. In fact, much of the research conducted to develop the analysis and solutions was spent on small manufacturing companies or similar machine shop companies under the same constraints. For example, Toyota was heavily researched as the Toyota Motor Company was under the same constraints at their beginning that our company is currently under. Toyota developed the Toyota Production System as a result of a manpower and capital constraint post World War II. Therefore, we thought it was appropriate to research their techniques for operating in this similar highly constrained environment.

Without the ability to look outwards for solutions to capacity constraints, our company had to look inward to find a way to grow capacity. Any company or system under similar constraints will benefit from following the strategy implemented in this research. Begin by quickly analyzing your Bullwhip Effect. Perhaps some of it can be quickly reduced by just simply becoming aware it. Then, we encourage you to start as close downstream to the customer as possible. This way, as you reduce the variations and gain capacity, the positive effects will have a domino effect felt by the rest of your company.

Our company chose to keep the Finish Good Inventory at its very high level and even added more through the Sell 1, Make 1 technique outlined in this paper. This way, the company could confidently take risks and make changes without worry that they've made an irreversible error. This gave the company the confidence to explore new ideas and to develop a new culture of process improvements and teamwork without affecting the customer experience.

With that strategic safety stock in place, our company conducted events like a companywide 5S Sorting Day in which the entire Manufacturing Department stopped operations for two hours and removed all the unnecessary tools and equipment at their work stations. They finally have enough slack to focus on cross training and process improvement. With reduced workload due to improved efficiencies, the company's employees reaped the most benefits as the company posted its highest summer vacations days in recent memory. Additionally, their daily lives became less frustrating as their jobs were more stable due to the reduced variations.

By reducing variations, we improved efficiencies, gained capacity, reduced costs, improved teamwork, and developed a more pleasant workplace environment; the company is on its way to be a world class manufacturer. Yours can too.

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Appendix A – Calculations

Lead Time Calculations

The lead time calculations are an estimation due to the current processes in place. Due to various reasons, the manufacturing planner would reorder a SKU before the calculated reorder point explained in Chapter 3. From here, the SKU would go through the first operation, the saw, and then wait in queue before the next operation. The planner would hold the SKU here until it was identified as needed. Once the planner released the SKU, it would naturally flow through the remaining operations.

Because of this manual process of holding the SKUs in queue, the data showed that the time from the saw to the last operation were highly variable as the system was not in control. For this reason, we decided to calculate the time from the first operation after the saw to completion. Then, knowing the saw operation always takes one day to complete, we added one day to this time. Essentially, what this did was remove the queue time between the operation. But this method is still not an accurate lead time as the queue has been removed from the system, even though in reality it is still there. But the result is a more accurate representation of how long the SKU could take to get from beginning to end.

Recalling that the lead time is used to calculate the safety stock and min to get the reorder point, we can use this information to learn if the new re-order points are too high or too low. Essentially, after the company has implemented the Periodic Review Policy, we can use the data to measure to see if our estimation of the lead time above was correct or not. If there is still a significant amount of queue time, then the re-order point is too high because there is too much WIP for the system to handle. But if there is significant amount of stock outs and there is no queue time, then the re-order points are too low and will need to be adjusted to order it earlier.

Cycle Stock and Safety Stock Modifications

The Periodic Review Policy discussed has some slight modifications due to policies in place within the company. Currently, there is no set review policy and no set lot size policy. Due to this, estimation of those must be determined before proper inventory levels can be established. Utilizing the data from the past year, we learned that the lot sizes were constantly changing, but to no clear pattern. Therefore, we decided to take the average lot size over the entire year to establish our lot size for the calculations.

With this calculation determined, it became policy to not change the lot size. With set lot sizes and daily demand, we now understand how often the review period is. This relationship is understood from the inventory equations presented in Chapter 2 and seen below. Once this relationship is understood, we are able to use the calculated review period to complete the equations and analysis.

$$Cycle\ Stock = \frac{Q}{2} = \frac{r\mu}{2}$$

Model Data Points

The model has to make some assumptions due to a lack of real data or information. The day to day inventory levels are unknown for 2018. In fact, the only time the inventory levels are known are on the first day and last day of the year. But through sales data, reordering dates, and missed orders due to stockouts, we were able to get an estimation of the inventory levels for each SKU.

Additionally, since the lead times for the SKUs are largely based on the amount of queue time, and thus, the product mix in the shop, we chose to use the average lead time from re-ordering to complete in the model. This way, we don't bias the model to be more or less productive due to the product mix. The lead time calculations are further discussed below.

Queue Time Calculations

The queue calculations discussed below is how we estimated the cumulative queue time in MFG, and is not specific to queue time discussed above. The ratios of machine setup time to production time to queue time is an important relationship to understand what the WIP is doing while in the system. For that reason, this section is dedicated to understanding how the ratio was calculated in the Chapter 3 section.

From the data set, we have the total setup hours and total production hours. These two times, along with the total time from re-order to stock, gives us a chance to see how much time the SKU lot is in queue. The lead time calculation from Chapter 2 is seen below:

$$Lead\ Time_{batch} = Total\ Processing\ Time + Total\ Queue\ Time \qquad (2\text{-}9)$$

Since we can measure the lead time and total processing time, we can solve for the total queue time. With queue time calculated, we now have all three times to determine the ratios.