Cycle Time & Cost Reduction in a Low Volume Manufacturing Environment

by

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ABSTRACT

Research was conducted on site at the Optical Storage Products business unit of Eastman Kodak Company to determine and implement methodologies for reducing cycle time and cost in a low-volume manufacturing environment (less than 1000 units annually).

A Kanban production system was successfully implemented to help reduce cycle time by 75%. The design and operation of the Kanban system was tailored especially to low-volume manufacturing, and is compared with a Kanban system design methodology for higher volume manufacturing.

Cycle time tracking was performed for an overall production process and individual process steps. It was discovered that cycle time tracking for the overall production process was extremely effective; however, the low-volume manufacturing environment created significant difficulties for measuring the cycle time at individual process steps.

A purchasing model was developed to determine optimal procurement policies and to reduce overall component costs. Three scenarios were run on the model to determine expected component cost reductions. This allowed a user to commit up to one, two, or four years worth of components from a supplier for low, medium, and high risk scenarios respectively. Expected component cost reductions determined by the model were 4.34% for the low risk, 8.94% for the medium risk, and 11.35% for the high risk scenarios.

Thesis Advisors: Stephen C. Graves, Professor of Management Science
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Finally, without the help of the Optical Head Flow Team, none of the results in this thesis would have been possible.

Optical Head Flow Team

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1. Introduction to Kodak

1.1 History of Eastman Kodak Company Film & Equipment

Eastman Kodak Company is widely known for its film manufacturing. When George Eastman started the company in the late 1800s, he quickly realized that film manufacturing was more profitable than camera manufacturing. This was because film manufacturing was a continuous process which benefited from scale economies. Additionally, since film needed replacement more often than cameras, a continuous demand provided greater revenues and profits. To generate high revenues from Kodak film sales, Eastman marketed and sold film in international markets obtaining large scale economies. This early expansion made Kodak one of the most recognized household names in the world.

As Kodak built an entire infrastructure for film manufacturing, it continued making cameras as a catalyst to spur film sales. Eastman realized early that camera manufacturing did not require the intensive capital requirements that film manufacturing needed[1]. By creating the capital intensive sensitized goods (film) manufacturing structure, Eastman was able to create a significant barrier to entry for other firms. While many companies fought for the low margin camera business, Kodak enjoyed higher margins on its film production. These ideas still exist in some portions of Kodak today.

By the late 1980s, Kodak continued to focus on film to keep profits high. The equipment division served two purposes. To provide high-end processing equipment which **supported, not replaced,** the film industry and low-cost consumer cameras to spur film sales. During this time, Kodak conducted research in digital imaging. The primary purpose of this research was to keep Kodak ahead of competitors in digital technology, so

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[1] Loyd, Bernard. Eastman Kodak Equipment Manufacturing. MIT Sloan School of Management. 1990.

if digital imaging surfaced as a replacement for sensitized goods, Kodak would be ready. This research has provided world leadership in many digital technologies. In fact, Kodak receives more patents annually than almost any other company in the world. Unfortunately, discrete component high-volume manufacturing capabilities have not followed suit. This is primarily because Kodak has not focused resources on discrete component manufacturing. Similarly, the low revenues generated from low-volume equipment manufacturing have not created a need to focus significant resources on improvements either.

When George Fisher became CEO in 1993, he brought a new vision for equipment to Kodak for the first time in the company's 100+ year history. He realized digital technology was reaching a point where it was within reach of replacing the huge film market. As the former CEO of Motorola, he brought with him experience in high-volume discrete component manufacturing. For the first time in history, Kodak had a CEO that was ready to focus equal attention on both film and equipment. Fisher encouraged Kodak's equipment division, Kodak Equipment Manufacturing Division (KEMD), to begin developing high-volume digital products. While many worry that this focus will decrease film sales, Fisher believes that digital imaging will complement film sales, creating a larger imaging market.

The challenge Kodak faces is enormous. With huge electronics companies tapping into the digital imaging market, Kodak needs world class discrete manufacturing capabilities soon. Competitors from Epson to Hewlett-Packard are entering this market. Kodak's history of providing state-of-the-art technology and research does not transfer directly to manufacturing. This manufacturing capability has to be developed, something Kodak is focusing heavily on now. High-volume manufacturing obviously receives more attention than low-volume, since revenue generation is greater for higher volumes. George Fisher has created metrics to improve Kodak's high-volume discrete component manufacturing capabilities. As high-volume units discover new ways to improve their capabilities, low-volume units have followed with similar practices. The purpose of this thesis is to discover if low-volume manufacturing has special needs due to the nature of its volume. Do high-volume practices apply to low-volume all the time? How does low-volume meet Fisher's goals, specifically in cycle time and cost reduction?

1.2 Optical Storage Product Line

The research of this thesis was conducted in the Electronic Imaging and Equipment Manufacturing Division of Kodak, in the Optical Storage Products business unit. This division is responsible for producing devices that store data optically. Three main products are produced in this division, the KODAK DIGITAL SCIENCE OD System 2000E Automated Disk Library, the KODAK DIGITAL SCIENCE Writable CD System / 6000, and the KODAK Disc Transporter. For the remainder of this thesis, these products will be referred to as the ADL 2000, 6X-writer, and Disc Transporter, respectively. A new product, not yet on the market, is also discussed. It is officially named the KODAK DIGITAL SCIENCE OD System 2100 and will be referred to as the ADL 2100.

The ADL 2000 is a jukebox type data storage system which stores up to 130, fourteen inch diameter, optical disks. Each disk is capable of storing up to 14.8 gigabytes. With 130 disks in the system, the ADL 2000 stores almost two terabytes of information, the largest data storage system in the world. The unit is approximately the size of two refrigerators, standing over six feet tall, three feet deep, and six feet wide. The ADL 2000 is a modular system, which allows customers to buy only what they need. This modularity provides different combinations of the number of disks and disk drives contained in the system. Customers can choose the number of disk drives and disks they need in the system, within certain limitations. Typical customers include large financial institutions such as banks, medical facilities such as hospitals, and government agencies such as the Internal Revenue Service. This product is a low-volume manufactured item, with sales under 200 units annually.

The 6X-writer is a small machine capable of writing to compact discs. It is slightly larger than a home CD player, with a single drawer capable of holding one compact disc at a time. This device was developed to support Kodak's Photo-CD player launched in the late 1980s. The 6X writer is the fastest machine in the world for writing information onto compact disc. It is currently marketed toward customers who require production capabilities for compact discs with unique information. These are cases when it is not advantageous to create a master mold for a compact disc. Annual production of this unit is under 1000 units a year.

The third product produced in Optical Storage Products is the KODAK Disc Transporter. This device is used in conjunction with the 6X-writer for automatically loading compact discs in and out of the 6X-writer. This eliminates the need for a human operator when producing compact discs. The device is capable of holding a palette of 75 compact discs. Less than 1000 units are produced annually.

The ADL 2000 and 6X-writer both use optical heads produced by Kodak to read and write information to the optical media. These optical heads have the highest performance capabilities in the world for data writing speed, retrieval, and accuracy. The optical head used in the 6X-writer was developed to meet industry standards for compact disc technology, while the optical head made for the ADL 2000 uses a Kodak developed format, allowing for higher performance. In this thesis, the optical head for the ADL 2000 is referred to as the KOH 2000, the optical head for the 6X-writer is referred to as the KOH CD, and a new optical head for the future ADL 2100 is referred to as the KOH 2100. KOH stands for Kodak Optical Head. Total optical head volumes are under 2000 units annually.

Because the optical head is the technology limiting component for optical storage devices, this thesis focuses on production practices used to meet Fisher's goals while improving the manufacturing capabilities of the optical head line. It is believed that if Kodak can improve optical head manufacturing practices, the overall business will be improved since the optical head is the limiting factor in read/write speed, data storage density (bits/square inch), and cost. Therefore, concentrating on a new manufacturing process for optical heads serves two purposes. First, it improves the production capabilities of technology limited components. Second and more importantly, it provides a low-volume model for other low-volume lines to learn from and copy if applicable.

1.3 Fisher's Goals

George Fisher brought to Kodak three corporate goals that had been used successfully to return Motorola to one of the best discrete component manufacturing companies in the world. Motorola, famous for its six sigma (about 3.4 defects per million) goal, used cycle time, defect, and cost of quality reduction to incentivize practices which produce world class manufacturing.

When Fisher arrived at Kodak, his message was clear. "Over a three year time period, each manufacturing unit is expected to show a":

1. 10X reduction in cycle time
2. 10X reduction in defects
3. 2X reduction in the cost of quality

Definitions for the above three metrics are presented below.

1. Cycle time - Is the total time required to build a product. This includes supplier lead times, production time, and the time needed to distribute the product to the customer. This thesis concentrates on the production time, since internal efforts at Kodak have successfully tackled supplier lead times and distribution times.
2. Defects - A defect is any occurrence that does not meet design and/or customer requirements. They are recorded either on a per unit basis or per opportunity basis. The Optical Storage Products business unit uses the number of defects per unit to track internal and escaping defects.

3. Cost of Quality - The total cost of (poor) quality includes any action within Kodak that does not directly add value to the product. This includes the time and capital needed for end of line testing of products, inventory carrying costs, and other costs not directly adding value to the product.

These corporate goals are measured uniformly across the company. Manufacturing units provide charts known as "four-up" charts. The four charts provide defect, cycle time, cost (using learning curve), and customer performance trends (decided upon by each manufacturing unit) over the course of three years. Additionally, Fisher does not expect facets within Kodak to stop continuous improvement efforts once these goals are met; rather, new goals are established to continually challenge the manufacturing units. For example, Fisher's goals include a 10X reduction in defects within three years, but achievement of six sigma by the end of the decade.

1.4 Low-Volume Scenario

Meeting Fisher's goals in a low-volume environment presents challenges. The most obvious challenge is the lack of data provided by low-volume manufacturing units. Since volumes are low, the time required to collect sufficient data is significant. This thesis attempts to tackle two of Fisher's goals directly, and the third indirectly.

An attempt is made in this thesis to determine a suitable process for reducing ***production*** cycle time by 10X over three years. This is accomplished by improving existing production systems at the factory floor level. Secondly, any cost added to the product as a result of inefficient buying and delivery practices is considered a cost of poor quality. An attempt is made to identify such practices, and develop a model to optimize buying and delivery practices for a low-volume manufacturing unit, reducing product cost. This was chosen with the belief that inefficient procurement practices are one of the biggest costs of poor quality generated in the Optical Storage Products business unit. The third goal, defect reduction, is tackled indirectly since no data was collected by the author to determine the amount defects were reduced when new processes were introduced into a low-volume manufacturing environment.

1.5 Thesis Overview

This thesis begins by presenting a quick overview of the manufacturing process for Kodak optical head sub-assemblies. The optical head production line was chosen to conduct research on for two reasons. First, with the technology limiting component of optical storage products residing with the optical heads, any improvement in optical head manufacturing is a direct improvement to the overall product. Since no other company in the world has a similar performing unit on the market, Kodak can remain ahead in performance by improving its manufacturing capability of this component. Additionally, Kodak's engineering talent in optical head design combined with its patent protection create an entry barrier to competitors. Secondly, the optical head production line maintained the most challenging product mix, since it was the only line in the Optical Storage Products business unit factory producing multiple products on the same line. Therefore, any success with implementing a new production system on this line would most likely work on other lines within the factory.

Next, a discussion of production challenges is presented followed by a list of production methodologies considered to attack such challenges. From this list of methodologies, a production system was chosen and its implementation is discussed.

The optical head production line was used by the author and factory employees to implement this new production methodology into the factory for this project only. Other low-volume business units at Kodak have implemented their own processes to tackle Fisher's goals. This allowed a pilot production area to test and modify new production processes introduced into low-volume environments. Additionally, using a pilot process provided new production systems training to factory operators. The optical heads pilot process allowed "bugs" to be worked out of a new production system before transfer to other Kodak production lines. The goal was to improve the probability that the new low-volume manufacturing processes would be adopted by other Kodak production lines.

2. Optical Head Manufacturing Process

The following provides a brief description of the production process required to manufacture an optical head. The major process steps are listed in order of production, with the exception of the optical sub-assemblies description.

2.1 Kodak Optical Head

The Kodak optical head is a sub-assembly used in the final assembly of the ADL 2000, ADL 2100, and 6X-writer. The unit is approximately five inches wide, by five inches long, by two and half inches high. It consists of two major assemblies, an optical casing and electronic circuit board.

The KOH CD optical head is illustrated in Figure 1. The optical casing portion of the sub-assembly contains all of the necessary components to emit, detect, and direct infrared light from a diode laser to the media and back to a detector. The major components used in the optical casing are the lenses, laser, actuator, and detectors. The electronic circuit board provides all necessary power, control, and logic circuitry to effectively interface with the actuator, laser, and detectors.

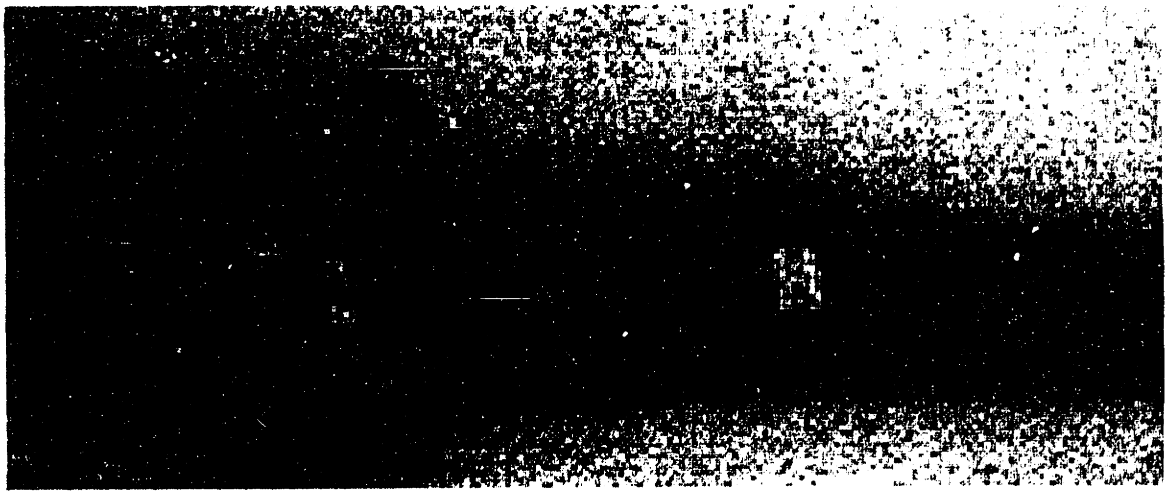

Figure 1: Kodak Optical Head

2.2 *Optical Head Assembly Layout*

Figure 2 illustrates the general factory layout for the optical head production line. The dashed lines indicate the location of production equipment. Factory personnel are free to move through any area not marked off by a dashed line. The arrows indicate the direction of product flow through the factory. No arrows are shown for sub-assemblies since the diagram becomes too busy with the additional arrows. Finally, the testing bay for the KOH 2000 product is adjacent (to the right of) to the main production flow shown in Figure 2. The amount of equipment used to test KOH 2000 heads requires substantial floor space, and thus is not shown in this diagram.

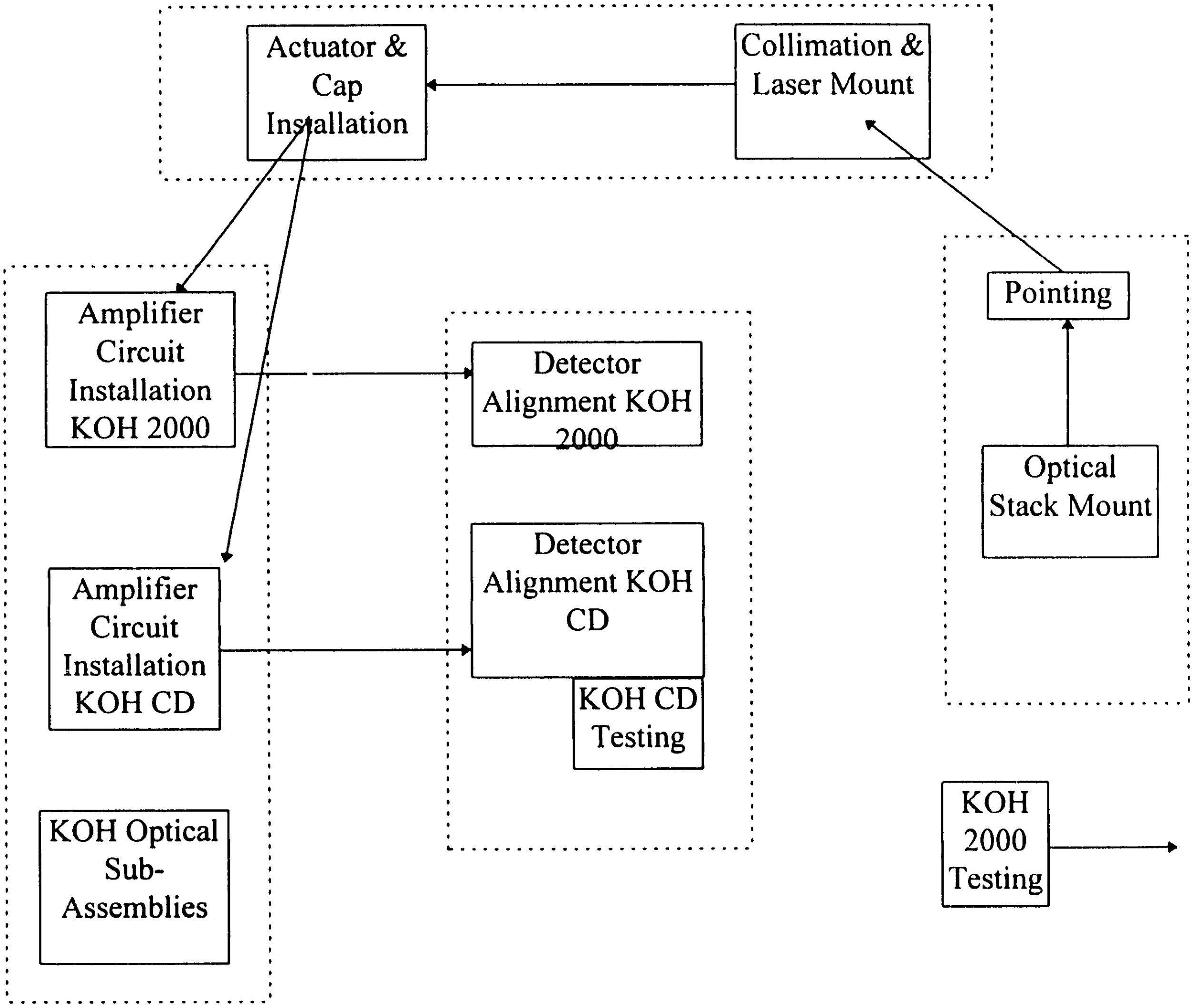

Figure 2: KOH Optical Head Production Layout

2.3 Optical Sub-Assemblies

The optical sub-assemblies that feed into the main production line are best characterized by two commonalties. First, production of these assemblies is governed by the needs of the main production line. As long as enough sub-assemblies are ready for each station, it is not necessary to coordinate sub-assembly production with main line production. Rather, as work slows down, operators use the excess time to build sub-assemblies for future production needs. Secondly, many of the sub-assemblies require a special adhesive which must be prepared each time a sub-assembly is made. Since the majority of the production time is in preparing the adhesive, large batches of sub-assemblies are produced at once.

Specific sub-assembly steps are not listed here, however, three main categories are present, laser sub-assembly steps, optical sub-assemblies, and actuator modifications. Laser sub-assembly steps include mounting the laser to a harness for later installation and preparing the high-frequency injection circuit for the optical head. Optical stack sub-assemblies include preparation of the front facet detector, cover glass, quarter wave plate, and cylindrical lens. These steps generally involve using an adhesive to glue an optical component into a housing. Finally, actuator modification steps provide pre-testing and sorting of actuators for the different optical heads.

2.4 Optical Stack Mount

Optical stack mounting includes preparing an aluminum housing and placing an optical stack and group of lenses in this housing with an adhesive.

2.5 Pointing

The pointing step assures the optics in the previous step cured properly, and did not fall out of alignment. When alignment errors are detected, the stack is removed from the casing and sent back to the optical stack mount step.

2.6 Laser Mount

The installation of the laser occurs next. This is done in conjunction with the following process step, collimation. An ultraviolet adhesive is used to permanently fix the laser onto the aluminum casing.

2.7 Collimation

The collimation process step is used to assure the laser is positioned properly on the optical head. The shape of the laser spot and alignment are checked to ensure the laser is properly fixed on the optical head.

2.8 Actuator and Cap Installation

An actuator is installed on top of the optical head next. This component is used to focus the laser on the media and to keep the laser within track. Tracks are concentric rings on an optical disk where the information is stored. A cap (cover) is installed on the actuator to keep the optics dust free.

2.9 Amplifier Circuit Installation

This process step marries the optical portion of the head to an electronic circuit, since the optical information needs to be processed into electrical signals.

2.10 Detector Alignment

Detectors are added to the optical head to perform two functions. One is to read data from laser light reflected by the media. The other is to provide continuous feedback to the laser's position on the media, so fine tuning adjustments can be made. The detectors are aligned and fixed to the optical head aluminum casing. Additionally, the necessary electrical connections are made to the amplifier circuit.

2.11 Testing

Now that the optical head is completed, testing occurs to ensure the optical head meets design specifications. This testing varies greatly depending upon the head type, KOH 2000, KOH CD, or KOH 2100.

3. Challenges with KOH Manufacturing

3.1 Production Planning - Not Optimized

The Optical Storage business unit used an MRP-II scheduling system to send weekly production needs to the floor. The factory floor would then produce enough optical heads of different types to meet the weekly demand. There was no tool available to help operators determine the product mix which optimized production. Since different product mixes created capacity constraints in different locations on the production line, it was not intuitive how to schedule products through the factory. In June of 1995, operators in the factory would take weekly demand schedules generated from the MRP-II system, and lay up optical stacks in batch sizes equal to the capacity of tooling at this step. Production planning was not optimized to factory capabilities.

For example, suppose eight KOH CD, and ten KOH 2000 were needed for a given week. With eight tools available, eight KOH CD stacks were laid up on Monday. Next, eight KOH 2000 stacks were laid up on Tuesday. The remaining two KOH 2000 would be laid up on Wednesday. Any optical stacks not passing the pointing station were re-mounted, allowed to cure, and tested until passing for the remainder of the week. This procedure did not treat an optical stack failure as an opportunity for root cause analysis, rather, it was treated as standard procedure. Additionally, optical stacks that failed once were more likely to fail again. It was possible to have a large number of optical stacks reiterating this process, creating excessive work-in-process while accumulating cycle time.

These large batches then moved through the production system, creating a capacity constraint through each process they traveled. Additionally, if KOH CDs, produced first in the week, were moving through the production system, operators skilled with KOH 2000 production were not fully utilized until the KOH 2000 optical stacks completed the optical stack mount station. Operator idle time coupled with inefficient batch sizing required more work-in-process to provide unoccupied stations work. Finally, the MRP-II weekly schedule was not representative of customer demand, but a forecast of demand in the future. Therefore, not only was production sub-optimally batched, but it did not meet actual market demand.

3.2 Cycle Time too Long

Since cycle time reduction was one of the corporate measures, the Optical Storage business unit was tracking cycle time before June of 1995. There are basically three components to cycle time: supplier lead time and parts receipt, production, and distribution. The total cycle time can be extremely long. Measuring the cycle time from the supplier, through the factory, into the distribution channel to the customer provides useful data on the major contributors.

Since reductions in supplier lead time and distribution channel time are accomplished in a similar manner for both high- and low-volume, this thesis focuses on reductions in production cycle time. By learning methods for reducing the production portion of the total cycle time, the Optical Storage business unit can transfer this technology to suppliers. This inevitably will allow suppliers to reduce their lead times.

3.3 Variability - High, Problems Hidden

The variability in optical head production is high. Process times for process steps vary greatly from one unit to the next. Many of the causes of this variation are unknown. The ramifications of this variability include long cycle times, increased product cost, and poor quality. With high levels of work-in-process, many of the problems are hidden. This tends to incentivize a behavior which tolerates the high variability as acceptable, or expected.

3.4 Cost of KOH too High

Low-volume manufacturers do not have the economies of scale to drive costs down in the same manner as high-volume ones. With the complexity of the Optical Storage products higher than most consumer products, the engineering effort required to design new products is similar to that of higher volume consumer products. The high number of components needed for production also require equivalent numbers of procurement and quality personnel to that of higher volume manufacturers. Additionally, long cycle times increase work-in-process, which increases cost. Variability creates poor quality, which creates costs, many of which are hidden. In addition, with over 70% of product costs related to components, the purchasing policy is analyzed to determine possible areas for improvement.

4. Methodologies Considered

4.1 Cycle Time and Defect Reduction

4.1.1 Tools Available

Different production methodologies were considered to help achieve Fisher's goals for a low-volume environment. MRP-II, Kanban pull production, and the Theory of Constraints (drum, buffer, rope) were compared to determine which methodology best met the needs of Optical Storage.

4.1.1.1 MRP-II

The Optical Storage business unit uses an MRP-II production system to move product through the factory. This system allows for exact accountability of all components and finished products. While the MRP-II system is accurate at accounting for components and finished products, it does not provide information on work-in-process or production scheduling. This causes excessive increases in work-in-process, which lead to long cycle times and hidden variability.

4.1.1.2 Theory of Constraints

The theory of constraints from The Goal[2] was considered to help improve production practices within the factory. Using a drum, buffer, rope technique, the Theory of Constraints suggests identifying the bottleneck in production (drum - production rate), placing a buffer immediately before the bottleneck (buffer - inventory) to keep the process step busy, and pulling production through the factory at the rate of the bottleneck's production (rope - signal to build).

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[2] Goldratt, Eliyahu M. The Goal. North River Press, Inc. 1992.

Unfortunately, multiple product types (KOH CD, KOH 2000, and KOH 2100) all have different process needs, and more importantly, different process times. This creates a moving bottleneck, dependent upon product mix. Since the bottleneck is not stationary, the theory of constraints is difficult to implement. Even when one process step was identified as a bottleneck, variations in product mix eliminate the simplicity and benefits the Theory of Constraints provides to production. Multiple buffers are needed to accommodate possible product variations.

4.1.1.3 Kanban

A Kanban system provides a solution to product mix problems. As demand for different products varies, the Kanban system has the ability to focus attention on work that is needed to meet demand. A drawback is the increased work-in-process required, when compared with the Theory of Constraints, to attain this flexibility.

4.2 Optical Head Cost Reduction

Over 70% of the optical head cost is the cost of components sourced from suppliers. Current buying practices in Optical Storage attempt to minimize these costs by classifying components using an ABC system, where A components are the most expensive and C components are the least. There is a concern among Optical Storage Products managers that this buying practice does not minimize component costs.

The tools available to better understand component costs are generally developed for high-volume manufacturers. With this in mind, a model is needed to accurately provide an optimal component buying strategy for low-volume manufacturing.

4.3 What we Used

4.3.1 Kanban / MRP-II Mixed Model

This thesis attempts to provide a compromise that takes advantage of the benefits of two of the above systems. The Kanban system is the dominant production methodology used, and was chosen for its flexibility with multiple product types. The MRP-II system clearly accounts for components and finished goods better than any other system. This provides accurate records for management to track components, costs, and other necessities. Finally, an attempt is made to identify process capacities and times, so that bottlenecks can be managed better.

While the heart of the production system introduced to optical head manufacturing is Kanban in type, the supporting MRP-II systems provide a solution to enabling low-volume manufacturing units to successfully meet George Fisher's goals. This is discussed in the following chapters.

4.3.2 Low-Volume Purchasing Model

A low-volume purchasing model is developed to provide detailed cost information to management. The purpose of the model is to identify overall unit costs, so they can be minimized. The model is developed by using an economic order quantity (EOQ) backbone which aids buyers with identifying blanket order sizes, delivery lot sizes, and delivery schedules. Additionally, it provides a comparison against current buying practices, and calculates expected annual savings for each component. Finally, the model provides sensitivity analysis so risk can be determined.

4.3.3 Formation of an Optical Head Flow Team

An Optical Head Flow Team was formed to implement the Kanban system. The team consisted of eight production operators, one assembly leader, two process engineers, one buyer, and the author. A team approach provided the best results since implementation strategies required interaction with different functional groups within Optical Storage Products. Since the pilot process implemented into Kodak's optical head manufacturing line was designed to be transferable to other production areas within Kodak, it was important to provide training to a group of cross functional employees who could take complete ownership of the process. This team was expected to aid implementation of the pilot process in other portions of the factory.

5. Kanban Implementation

5.1 Kanban System Design

Kanban systems are used successfully in high-volume environments. The challenge presented to the Optical Head Flow Team was the application of such a system in a low-volume environment. One of these challenges the team faced included accurate estimations of build times and yields. Because the weekly production volumes were less than thirty optical heads a week, it was difficult to collect trend data for the different process steps. Since many process or part problems seem to occur randomly, it was difficult to predict when a process step would produce a defect. When defects did occur, many times they occurred on successive products moving through the station. For example, the first three optical heads to pass through the station may be defect free, while the following three might all contain defects. Although the average yield of the process step is 50%, this value does not provide a good representation of the process step. Because the cycle time for the process step is long, the three failures basically cause a line shut down. To confuse issues further, since the production line moves so slowly, it is not clear the line is shut down and operators would continue to build product earlier in the process, building up work-in-process.

Many divisions within Kodak were in the process of implementing demand flow manufacturing. This is described by John R. Costanza, in The Quantum Leap. This book is geared toward demand flow manufacturing processes for higher volume production. An attempt was made to implement a Kanban system using Costanza's concepts. This would allow the team to learn some of the complications low-volume manufacturing presented when trying to implement Costanza's concepts for Kanban system design. Costanza does not include a method for determining Kanban placement on the line, but he does discuss in considerable detail Kanban sizing and signaling.

The process steps for constructing an optical head were documented by the team and placed into a spreadsheet to calculate throughput and capacities. These process times are shown in their spreadsheet form in Appendix A. For each process step, the following data was gathered:

1. Labor Minutes - The amount of labor (hands-on) time required for the process step.
2. Unattended Minutes - The amount of time required (without a person) for the process step. Twelve hours of glue drying is a common example.
3. Rework % - The amount ***of time*** required in rework for a given process step. This ***does not*** represent the percentage of components requiring rework. An average of 50% rework for a one hour process step (labor + unattended) indicates that, ***on average***, a component requires ***one and a half*** hours total (labor and unattended) for a process.
4. Labor Capacity - Indicates the maximum amount of stations that allow laborers to work in parallel on a given process step. In most cases this is one.
5. Unattended Capacity - Indicates the number of units that can occupy a process step simultaneously during Unattended process minutes. This mostly includes units in automated testing stations or curing jigs for glue drying.
6. Utilization Factor - This row was entered into the spreadsheet to allow for a linear program[3] to optimize product flow through the factory. A 1 indicates the station is manned 100% of the time, while a .25 indicates the station is only manned for 25% of a work week (this obviously only refers to labor process times, not unattended process times). The linear program automatically adjusts all of these utilization variables when run. The

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[3] A linear program is a mathematical model used to help identify an optimal solution in a linear system with multiple variables. This thesis does not discuss the use of linear programming. Flexibility was added to the spreadsheet to allow for linear programming in case it was needed in the future. The Optical Head Flow team did not have a need for it. With a higher product mix, it is feasible that linear programming could be used to aid production scheduling for an MRP-II system.

spreadsheet in Appendix A does not illustrate an output of a linear program run.

7. # Cycles for Unattended - This indicates the number of units (daily) which can be processed in one unattended capacity step. The Unattended Capacity multiplied with this number provides the maximum number of units which can be processed daily (unattended).
8. Throughput - Both hourly and daily throughput is provided on the spreadsheet to help production identify possible bottlenecks. The throughput calculation is a factor of the Utilization Factor above.
9. Cycle Time - This provides the cycle time in hours for a given process step.
10. KOH 2000 / 2100 / CD - These three rows are used in the linear program to assign stations to a given product. This allows process steps to be changed, added, or deleted without altering the spreadsheet drastically. A 1 represents that the optical head must go through the process step, while a 0 indicates that it does not.
11. Cumulative Cycle Time - This shows the cumulative cycle times for the three products. The subassembly stations are separated from the main build process. At Stage 1, the cumulative cycle time begins at zero. Most sub-assembly process steps can be completed in parallel, so the cumulative cycle time is misleading in this case. Production steps must be completed serially as listed in the spreadsheet.

All values of 0.01 are used to simulate a zero. This helps to avoid division by zero errors in the calculations. Some capacities are almost infinite; however, values such as 50 or 100 are entered on the sheet. Because these capacities are not constrained, the calculations are unaffected.

The bottom of the spreadsheet allows the user to enter the weekly expected production. This helps determine capacity constraints and provides useful information on product mix concerns. Appendix A shows six KOH 2000, ten KOH 2100, and eight KOH CD optical heads entered into the sheet. Below lists the weekly labor hours available given the number of employees, shifts, and the amount of work hours per shift. Production times are also listed for building one of each optical head (in labor time only). Separating labor from unattended process times allowed the team to better understand the production constraints.

The Stages listed across the top of the spreadsheet represent the breakdown of the Kanban stations the optical head flow team decided upon. The operators had most of the input on Kanban placement within the factory. Most stations are governed by overnight cure times for adhesives. This provided a logical completion point for the different stations. Station (Stage) 2 had an overnight cure when the Kanban system was installed in the factory. The operators discovered the cure step in this station could be moved to Station 3, so it was removed from Station 2 on the spreadsheet. Sub-assembly process steps are separated from the main product flow and are generally characterized by batch production. For example, 25 sub-assemblies may be made at one time, since the majority of the cost and time is governed by preparing the adhesives. Once the adhesive is prepared, it is simply a matter of gluing the sub-assemblies together. Additionally, sub-assembly steps are separated because most of the steps can be completed in parallel with each other.

Since one of the corporate measures includes a 10X reduction in cycle time, it was imperative to minimize work in process on the factory floor. Using Costanza's Kanban equation, an attempt was made to reduce work-in-process with the design of the Kanban system. His equation for Kanban sizing is listed below[4]:

$$\text{Kanban Size} = D \times Q \times R / (H \times P)$$

where:

D - Daily production rate per product per shift.

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[4] This equation was taken from <u>The Quantum Leap</u> by John Costanza, page 124, Published by the JIT Institute of Technology.

Q - Usage Quantity per product. If a unit only uses 1 of a given component, Q=1. If a unit uses 2 of a given component, Q=2. This can also be used for yields. If a yield is 50%, then Q=2 if the unit requires 1 component.

R - Replenishment time in hours.

H - The number of labor hours per shift

P - The quantity the supplier packages components (mostly used for establishing Kanban sizes with external suppliers)

When process times listed in Appendix A were used with the Costanza's equation, Kanban sizes were calculated which seemed too large. Since unattended process times were significant in many process steps, the replenishment time R was unfairly given a high value. For example, the optical stack mount required a twelve hour cure. While this value was added into the replenishment factor, the number of labor hours per shift remained between six and eight. This was clearly not a true representation of production. Since production (adhesive curing, testing) included processes which did not require human labor, it was necessary to determine another way to calculate Kanban sizes for the factory. Additionally, the calculation needed to be easy to use, so any member of the team could resize a Kanban if necessary.

It was necessary to group the process steps into stations for the Kanban system. To keep work-in-process to a minimum, the team decided to balance the station process times. In order to attain similar process times for each station, individual process steps were moved between stations until the stations were relatively balanced.

The number of stations was determined, in part, by the number of operators. A Kanban production system with twenty stations and five operators would create excess work-in-process, since only five of the stations are manned at any one time. Conversely, a Kanban production system with two stations and five operators has the potential of leaving operators without work. Even if multiple operators can man a station simultaneously, it may not be entirely clear what the flow of work should be. The definition of Kanban means, "visual signal". In order to assure the signal was visual and clear, the team decided to have about 20% more stations than operators. This allowed each operator to occupy a station during production. More importantly, this allowed operators to move to the unoccupied station if their station had no work left. It also provided alternative stations if additional operators were added during peak demand cycles.

Final placement of Kanbans within the production system was determined by the daily production, daily demand, and production times for each process. The team decided to group enough process steps together until a day's worth of production time was reached, creating balanced stations containing roughly one day's worth of total process time each. Since multiple product types were made in the factory, sizing Kanbans as a function of production capacity was extremely complicated. Instead, a simple approach based on product demand was used to help determine the Kanban size between stations. In order to develop a mathematical representation for determining Kanban sizing, the following expression was used:

$$\text{Kanban Size} = W/5 \times D \times Q$$

where

W - Weekly demand for a given product.
D - # of Days required to make a unit at a given station.
Q - Usage quantity per product. As before, the yield can be accounted for here. Our team decided to account for yield in process times instead.

There are a number of reasons the variables were chosen as shown above. First of all, since the factory was a low-volume production environment, the operators were accustomed to thinking in terms of weekly demand and daily production. Hourly production rates were not as clear. Secondly, since the spreadsheet indicated sufficient capacity for any one product, it was important to size the Kanbans based on expected demand. This allowed work-in-process to be minimized because the Kanban system was designed around demand.

Table 1 shows the calculated Kanban sizes between stations. Note that Kanban sizes are equal throughout the production sequence for a given product. This was a result of nearly balanced production stations. Although labor times may not be balanced between stations, total production (unattended included) all require about one day's worth of production time[5]. The placement of the Kanbans was decided mostly by the unattended process times, since they dominated overall production time.

BETWEEN	KANBAN SIZE		
STATION #s	KOH 2000	KOH CD	KOH 2100
1 & 2	2	3	3
2 & 3	2	3	3
3 & 4 (or customer)	2	3	3
4 & Customer	2	n/a	n/a

Table 1: Kanban Sizing for KOH Product Types

Table 1 shows Kanban placement between stations. This reflects the Kanban's presence, as a ***carrier*** between two stations. Kanbans are not located at any one station. The KOH 2000 optical head has four Kanbans, all with a size of two. As product is needed by Station 2, a Kanban of size 2 is pulled from Station 1. The units in this Kanban have successfully been processed through Station 1. Similarly, product is pulled from Station 2 and sent to Station 3 (Kanban = 2) when Station 3 has demand. Once again, units are *pulled* from one station to the next. Since production is balanced within the factory, two units ideally will move through the entire production process together, being pulled as a

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[5] Stations 1, 2, 3, & 4 for each product all had an overnight cure, or test, when the Kanban system was installed. The cure from Station 2 was moved to Station 3 after operators discovered cycle time could be reduced.

group of two, through the factory. This grouping size is determined by the size of the Kanban, which requires a factory which is fairly balanced.

Using the equation for Kanban sizing K = W/5 x D x Q, with a weekly demand of ten units (W = 10), process cycle time of one day (D = 1), and usage quantity of one (Q = 1), a Kanban size of two was determined. Since the production line was designed with stations balanced consisting of one day process times, all of the Kanbans are equal in size. The KOH CD and KOH 2100 maintain similar calculations, except weekly demand rates are between ten and fifteen. For example, the KOH CD weekly demand is about twelve units. With W = 12, a Kanban size of 2.4 is generated. Since this is not possible, the size must be rounded ***up*** to the nearest integer. Rounding down would create a Kanban system incapable of meeting weekly demand.

The KOH CD optical head did not have a separate testing station. Its testing was grouped with final production steps so work-in-process could be minimized. The KOH CDs combined testing time and final production process step were less than the one day's worth of process time, allowing the team to combine the two steps. With the KOH 2100 as a preproduction build, no test was established at the time the Kanban system was implemented.

Figure 3 shows the final Kanban system design. Although the process steps are identical for all three products through Stations 1 & 2, the components used in each product vary. For example, optical coatings on lenses are not the same, yet mounting the lenses in the castings is a uniform procedure for all three products. A dummy test station was entered for the KOH 2100, anticipating the future test process.

Station numbers were labeled in numeric order. Station 1 represents the first production step in the process, Station 2 the second and so on. At Station 3, the three different products require different production steps. The team wanted to maintain meaningful station numbers while differentiating the three products. Figure 3 shows the use of a decimal point after the Station number for attaining this goal. Station 3.1 is the third station for the KOH 2000. Station 3.2 is the third station for the KOH CD with Station 3.3 representing the KOH 2100. All X.1 designations refer to the KOH 2000 product line, X.2 refers to the KOH CD product line, and X.3 designations refer to the KOH 2100 product line. Station S was used for all three products to provide sub-assemblies to the main line. There are multiple Kanbans with different sub-assemblies between the sub-assembly station and main production line. All sub-assemblies were produced in a single portion of the factory to facilitate production.

An important element to this system is the equally sized Kanbans between stations. Note that the KOH CD line can produce three optical heads per day, since each station requires about one day's worth of production time (as discussed earlier). This indicates a volume of fifteen KOH CD heads per week. If demand increases or decreases, the entire Kanban system can be resized quickly to accommodate the new demand. If the Kanban size is increased to four, twenty KOH CD heads can be made per week. Similarly, decreasing the Kanban size to two limits weekly production to ten KOH CD heads. Operators can use the spreadsheet to determine capacity constraints, and add (or remove) capacity as necessary. This can be accomplished by adding (or removing) labor and/or equipment. The purpose of resizing the Kanbans is to ensure corporate cycle time goals are met, regardless of demand.

When demand drops, the excess work-in-process in the Kanban system increases cycle time significantly. By reducing Kanban sizes, the production floor is able to maintain low cycle times during lower demand periods. Similarly, since the Kanban system is optimized around expected demand, it is not capable of meeting higher demand rates without increasing in size. This simple adjustment allows the operators to size Kanbans based on current demand while meeting corporate cycle time goals. This places full ownership of operating the Kanban system with the operators. Management need only provide estimated weekly production needs.

Optical Head Kanban Production System

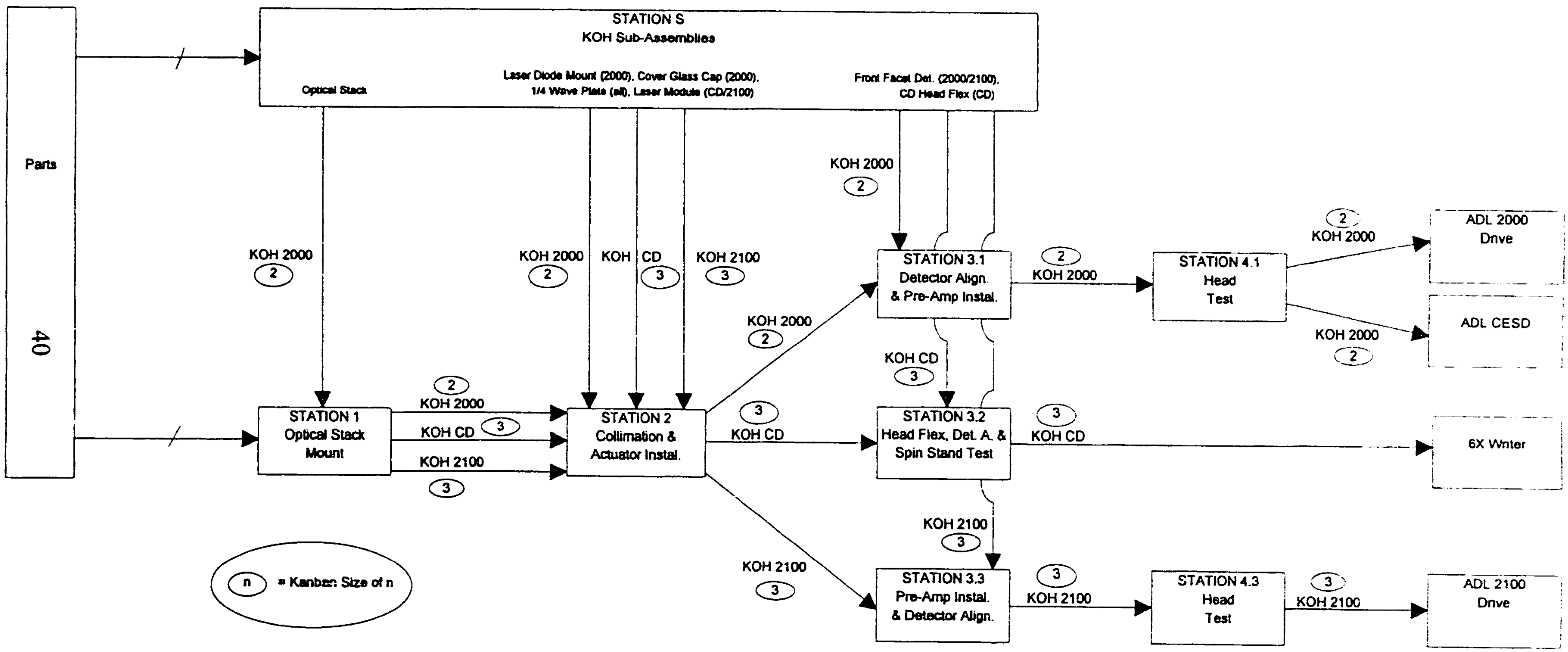

Figure 3: KOH Kanban System

5.2 Kanban Signals

5.2.1 Two Tray no Card

A two tray no card system was first chosen to move units between the Kanban stations and works as follows. There are two trays between Kanban stations as shown in Figure 4. Each tray holds multiple units, determined by the calculated Kanban size, k. Station n is signaled to send a full Tray 2 to Station n+1 when Tray 1 returns empty. Once this occurs, Station n produces k units to fill Tray 1. This process continues to repeat itself as empty trays are received by Station n.

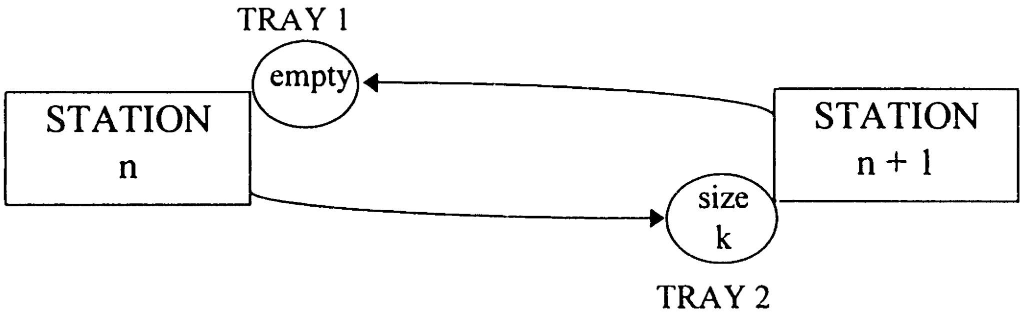

Figure 4: Two Tray no Card Kanban

This basic signaling technique is easy to follow on paper, but presents difficulties to low-volume manufacturing in practice. The team initially attempted this system, but quickly became confused when trying to track down empty trays. This system created a (violation) policy of filling "any tray in sight," so it was possible to fill both Trays 1 & 2 even if Station n+1 was not demanding product. For example, Station n+1 would return an empty Tray 1 to Station n, even though Tray 2 (full of product) was not needed yet. The team tried a policy of moving Tray 1 to Station n only when Tray 2 consumption began. With three different products in the factory, this became extremely confusing and resulted in multiple Kanban violations[6]. To counter this problem, the Optical Head Flow Team decided to develop a derivative of this signaling method. The derivative is illustrated in Figure 5.

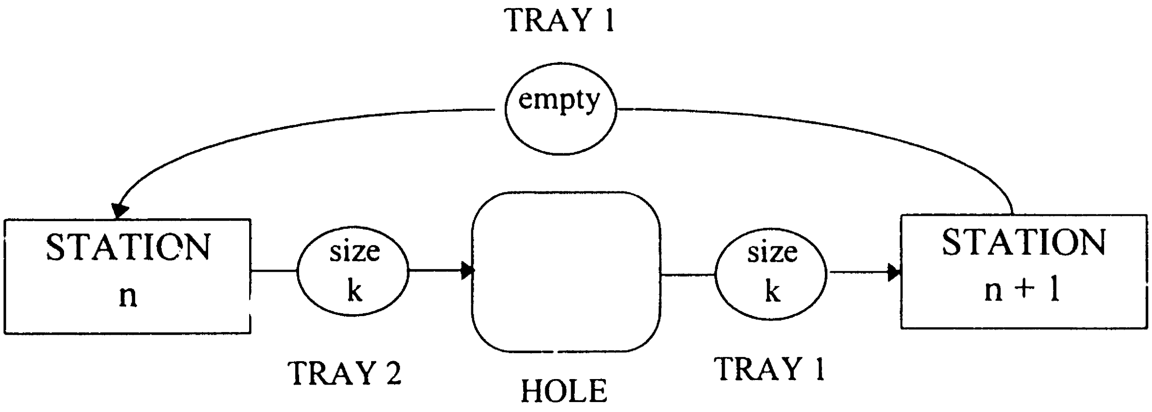

Figure 5: Modified Two Tray no Card Kanban

When Tray 1 is pulled from the "HOLE" to be used by Station n+1, this signals Station n to begin production into Tray 2 so the "HOLE" can be filled. A filled "HOLE" is defined by housing ***one*** filled Kanban tray. With this system, Station n begins production when Station n+1 begins consumption. When Station n+1 completes its consumption, Tray 1 is returned to Station n. It is not filled by Station n until the "HOLE" becomes vacant again. Since the process steps were grouped into stations that were balanced (total production time), the production and consumption rates are similar. This provides an average work-in-process between stations equal to one Kanban size. As one unit is removed from Tray 1 by Station n+1, another is placed into Tray 2 by Station n. While this process appears more complicated on paper, it is easier to use in production. By following a rule of, "BUILD TOWARD THE HOLE," the operators know to produce when the "HOLE" is empty. Since this was a specified location on a shelf, it was easy to determine when production was needed.

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[6] A set of Kanban rules was developed. Violations were defined by breaking a rule. These rules are discussed later in the thesis.

5.2.2 Kanban Signs and Cards (Color Coded)

A variety of signals were used to help facilitate the smooth operation of the Kanban system. The most important signal of, "building toward the HOLE," discussed in the previous section, was complemented by highly visible "HOLES." Signs were used to identify "HOLE" locations as well as locations to store empty trays. This provided an orderly accounting for work-in-process at any given time. If a tray was not located in the "HOLE" or empty tray location, it was being processed in one of the stations.

A color coded system was used to identify the three product types in the factory. Since the products looked identical at certain stages in the process, it was necessary to visually separate them. All products used color coded folders to maintain production information (test data, defect tracking, etc.). Color coded signs were used in the factory to indicate "HOLES" and empty tray locations. Finally, color coded Kanban labels were used on the tray covers. The following color coding system was used for all folders, signs, and labels in the Kanban system:

1. YELLOW - KOH 2000 product line
2. RED - KOH CD product line
3. BLUE - KOH 2100 product line
4. GREEN - Engineering models, special production

Since R&D work was performed on the line with operator help, the team implemented a green color to denote engineering models. Green folders were used with such products; however, there were no green signs or Kanban labels in the factory.

The Kanban carriers were black, antistatic, trays with six compartments. Figure 6 illustrates the layout of the compartments. One optical head in production required one of the six locations in the tray. Unused locations were filled with foam to avoid placing an extra unit in the tray by accident. The excess compartments in the tray allow the operators to resize the Kanban system without having to purchase new trays. They need only change the Kanban label on the outside of the tray and adjust the foam inside accordingly.

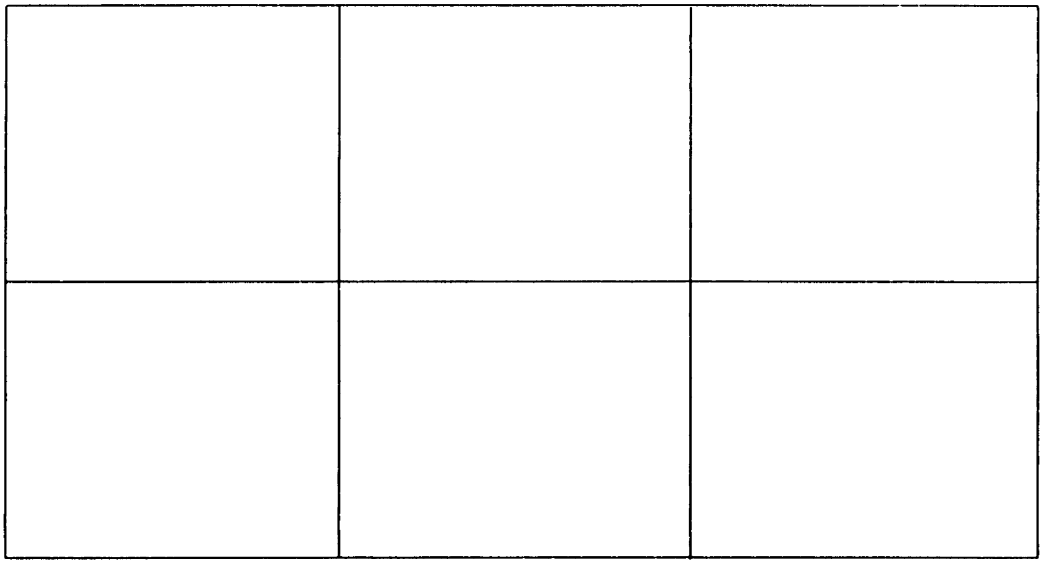

Figure 6: Layout of Kanban Tray (1-6 possible compartments)

Costanza suggests all Kanban labels provide the following information:

1. The part number.
2. Description of the part.
3. Kanban size.
4. Usage station (consuming).
5. Supply station (producing).
6. Bar code label.

The Kanban labels used for each tray in the Kanban system are shown in Figure 7. These are almost identical to Costanza's Kanban label suggestion. Three labels are shown for the KOH 2000 Kanban. These are ***actual size*** labels that can be slid into a plastic sheath on the tray covers. They are printed onto yellow paper (of course). This allows operators to easily relabel the Kanban trays if resizing is needed. Figure 7: Kanban Labels, is shown on the next page.

KOH 2000 Optical Stack Mount

P/N 3b2541
Optical Stack Mount and Pointing

②

Usage	**Supply**
Station 2	**Station 1**

KOH 2000 Collimation/Actuator Installation

P/N 3b2541
Laser Collimation, Pointing & Centering, Actuator & Cap
Alignment & Installation, Manual LI for Head

②

Usage	**Supply**
Station 3.1	**Station 2**

KOH 2000 Detector & Pre-Amp

P/N 3b2544
Detector Alignment, Pre-Amp Installation,
& BODE Plot Measurement

②

Usage	**Supply**
Station 4.1	**Station 3.1**

Note the labels contain five of Costanza's six requirements. Bar code lines were not added because the factory does not use a bar code system. Part descriptions were noted as most recent processes performed on the unit. The Kanban size is noted within the circle.

There has been no mention of an optimized production line layout purposely. The team discovered that in a low-volume production environment, there was very little (if any) return for optimizing the ***line layout***, since production moved so slowly. With all production confined to a 600 square foot room, transportation issues were negligible for such a low volume. The team did, however, rearrange the line to provide ample work space for operators.

5.3 Kanban rules based on above design

The following Kanban rules were established and posted in the factory.

KANBAN RULES

1. You can only fill the Kanban trays with the designated number of products specified by the label on the tray. This is the number in the circle.
2. Do not switch tray lids between the Kanbans. This ultimately will lead to confusion.
3. You are not allowed to have more completed products at your station than the size of the Kanban. For example, if you have a Kanban size of two, you can only have one filled Kanban at your station at any one time.... with two completed products.
4. Do not start to fill a Kanban until the **Completed Station X** location is empty. In other words, "**BUILD TOWARD THE HOLE.**"
5. There can be only **ONE** completed tray in the "**HOLE**" at any given time.
6. Place empty trays in designated locations.

5.4 Product Pull

In order to transition the Kanban implementation smoothly, a true make-to-order production was not used during the first month of operation. The schedule was obtained from the MRP-II (AIMS)[7] system, and used to pull product from the end of the line evenly. For example, if the schedule required ten CD heads by the end of the week, two per day would be pulled from the production area. This allowed the operators to familiarize themselves with a Kanban production environment without interfering with external groups in Kodak.

Once operators were familiar with the Kanban system, the team moved the production line to a make-to-order pull system. Product was only made when needed by customers. The customers were the ADL 2000 production line, ADL CESD (customer service, field replacements), 6X-writer production line, and engineering (KOH 2100). Since the ADL 2000 and CD-writers were in the process of moving to a make-to-order system as well, optical head production was not solely governed by schedule driven customers.

5.5 Vault/Inventory Changes

All components for the optical heads were stored in a central vault. Parts were released based on the MRP-II generated schedule, usually in large batch sizes. These large batch sizes of 6-24 did not provide an ideal delivery schedule for Kanban production. When many small parts needed to be picked each time a Kanban pull signaled production, the vault required an enormous amount of time to locate and pick the necessary components. Obviously, requiring the vault to pick components for two or three heads at a time was extremely inefficient.

To remedy the problem, the operators proposed a plan and moved all components to the floor. During a week of low demand, the operators moved in cabinets and provided

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[7] The AIMS system is the information used in the Optical Storage business unit. The MRP-II system is part of AIMS.

locations for all the parts on the factory floor. By moving all components to the floor, the operators were able to pick parts as needed. They also were able to see when quantities were low and if suppliers provided defective parts that the vault might not notice. The operators were now responsible for assuring accurate part counts on the floor.

Determining the final method for accurate parts accounting was still unresolved at the time of this thesis writing; however, a trial procedure for counting parts was being studied. This trial procedure required operators to perform part counts monthly. They would then provide this information to MRP-II personnel, who entered the data into the MRP-II system. After two months of performing this trial procedure, there were no noticeable increases in part shortages. The accuracy of part counts were also maintained during this time period. Note that a two month time frame does not provide adequate data collection to support this conclusion with high certainty however.

5.6 Employee Training / Cross Training - Issues

Two separate training programs were necessary to insure success of the Kanban system. First, the employees were trained on the design and operation of Kanban systems. This began with the definition of, and reasons for using, a Kanban production system. The second training program required cross-training of factory floor operators. This effort was led by one of the senior operators on the floor, and did not require any input from the author.

Weekly meetings coupled with hands-on experience provided the training needed to transfer ownership of the Kanban system to factory operators. The Optical Head Flow Team attended the weekly meetings. The two month training program listed below was implemented before any changes were made to the factory. This allowed team members to understand and question Kanban production before placing it in the factory.

Training Program

1. Understanding the corporate goals set by George Fisher.
2. Kanban, cycle time, and defect definitions.
3. Choice of metrics for the Optical Head Flow Team which included a standardized procedure for measuring cycle time and defects.
4. A plan for phasing a Kanban system into a factory.
5. Different Kanban signaling methods, such as signs, labels, trays, etc.
6. Product pull and make-to-order definitions.
7. Identification (and elimination) of nonvalue adding processes.
8. Variability definition and identification.
9. Product scheduling through the factory.
10. Kanban system design and operation.
11. Cycle time data collection.
12. Graphical interpretation for cycle time data.
13. Microsoft Windows[8] (for use with automated data entry spreadsheet).
14. Line stoppage due to defective parts/processes[9].
15. What-if scenario training.

This training program provided the necessary tools for the team to operate the Kanban system on their own. Since time was spent discussing concerns and issues before the system was installed, the implementation was fairly smooth. After two months of operating the system, the team began to use their skills to spread the concept to three other production lines within the factory. At the writing of this thesis, these were on-going efforts.

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[8] Microsoft and Windows are trademarks of Microsoft Corporation.

[9] This was actually implemented two months after the Kanban system was installed. The KOH CD line was shut down for almost two weeks. Significant reductions in cycle time resulted. See Section 6 for more information.

6. Effectiveness of Kanban in Low-Volume Environment

Once the Kanban system was in place, data was collected to determine its effectiveness at helping to meet some of the corporate goals. On August 24, 1995, the Kanban system was installed for the optical head production line[10].

6.1 Work-in-Process Reduced

The team expected work-in-process to decrease significantly with the introduction of the Kanban system. The amount of work-in-process was monitored from August 24 to December 2. By counting the total number of KOH 2000 and KOH CD heads in production at 3:00 PM each day, a graph was generated to illustrate trends in work-in-process once the Kanban system was installed. Figure 8[11] displays the work-in-process over a two and a half month time period for the KOH 2000. The cause for spike in work-in-process after the installation of the Kanban system is uncertain. Since accurate data was not collected prior to the Kanban system's installation, the past level of work-in-process is unknown. Past production practices tended to create drastic changes in work-in-process as demand varied. Variation in the production system also created such changes. Additionally, missing components for the KOH 2000 coupled with high demand bled the system to a lower than average point when the Kanban system was implemented. It is believed that the work-in-process present in the system on August 24 was the result of a trough in the cyclical variance in work-in-process caused by multiple factors.

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[10] Cycle Time data has been altered to hide actual data.

[11] Figure 6 was generated by Professor Robert A. Shumsky, Xerox Assistant Professor of Operations Management, Simon Graduate School of Business Administration, University of Rochester. Dr. Shumsky was conducting research within the same division at Kodak, and generated the graph out of personal interest.

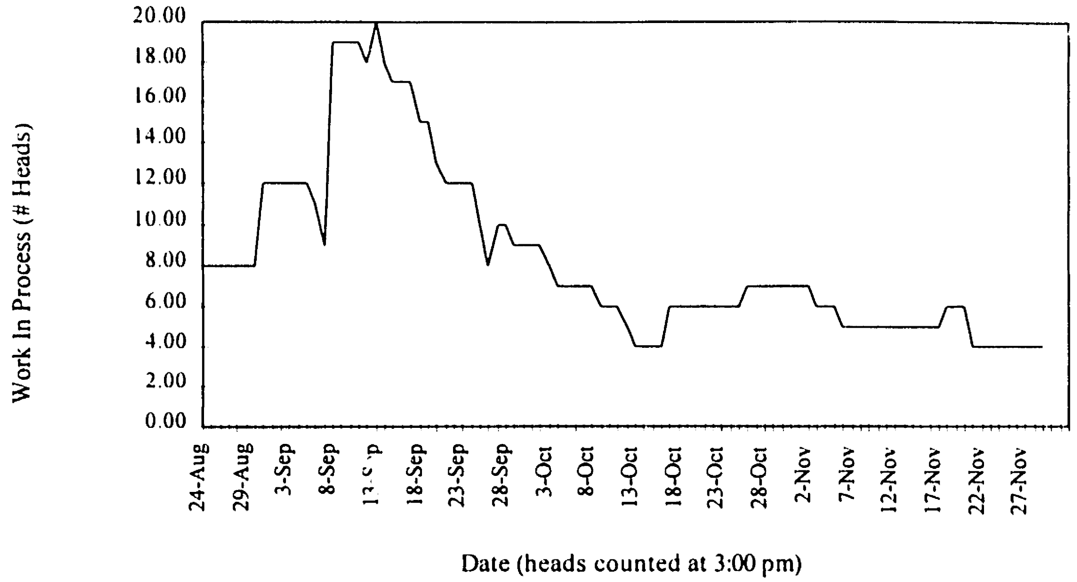

Figure 8: KOH 2000 Work-in-Process

The spike was caused by two factors. First, the operators were unaccustomed to the new Kanban system, and required time to become acquainted with it. Second, missing KOH 2000 components were finally delivered the first week of September, allowing new production to begin. With both factors combined, operators were concerned about meeting demand, and consequently stuffed the production line to insure demand would be met. Kanban production procedures were not followed correctly. This prompted the posting of the Kanban rules.

A similar graph was generated for the KOH CD. Note that work-in-process initially began at a high level and decreased over the course of one month. This was the type of data the team expected to see. Figure 9[12] illustrates this. The variance in work-in-process during November was the result of problem detection by the Kanban process. Two separate problems caused a shut down of the line for over one week. The CD spin stand and collimation station were both malfunctioning. During this period, the operators worked with engineers to solve both problems. The discipline the operators demonstrated during this time of crisis was a true testament to their ownership and understanding of the

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[12] ibid.

process. Work-in-process levels did not increase to earlier levels, even though the situation seemed very drastic at the time.

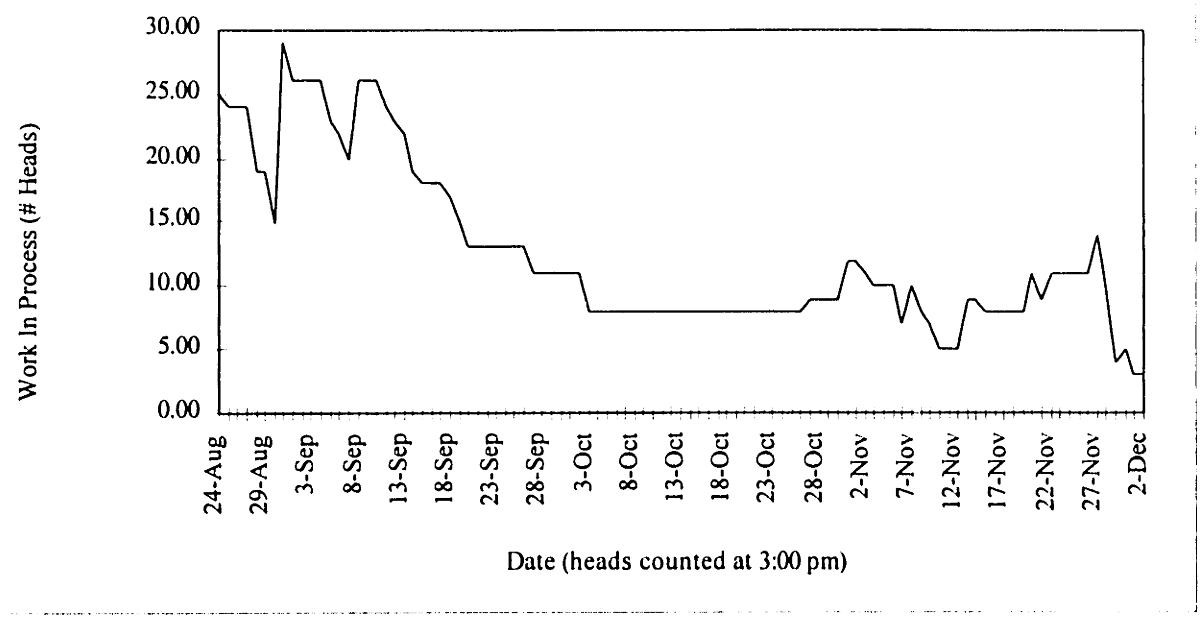

Figure 9: KOH CD Work-in-Process

6.2 Cycle Time Decreased

Because one of George Fisher's corporate goals was achieving a 10X reduction in cycle time within three years, the team focused considerable effort on tracking production cycle time for the optical heads. A necessary step toward cycle time tracking required defining the components of cycle time. Figure 10 illustrates all of the components the team believed attributed to cycle time.

All of the elements above the line were issues the team had direct control over when the Kanban system was implemented. The team decided to focus their efforts on this portion of the cycle time. Cycle time measurements began once a product was released from the vault and ended after the product was packaged and shipped to the customer. The four customers were the 6X-writer production line, the KOH 2000 production line, CESD for field replacements, and engineering for KOH 2100 products.

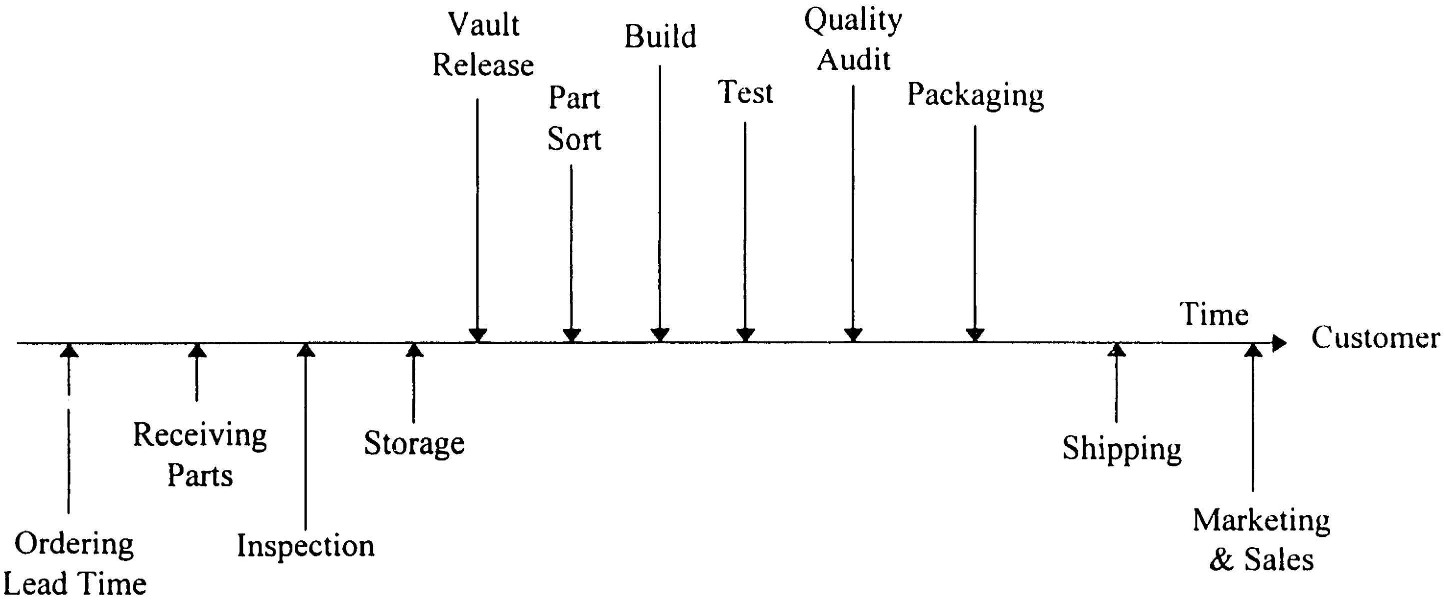

Figure 10: Components of Cycle Time

Soon after the Kanban system was installed, the operators became increasingly aware that the above cycle time contained too many nonvalue adding steps. The four steps of Inspection, Storage, Vault Release, and Parts Sort appeared to contribute to a significant component of cycle time. To counter this, the team proposed moving all optical head components to the factory floor. Since two of the steps, inspection and storage, were out of their control, the team (led by one of the operators) developed a plan and presented it to management. Within two weeks all components were moved to the factory floor. The new plan resulted in operators inspecting, storing, and sorting their own components. These tasks are now performed during periods when demand is low. This contributed to a 25% reduction in cycle time coupled with increased awareness of incoming component quality. Defective parts were found earlier since operators who used the components in production (thus they were more familiar with them) were now inspecting them upon receipt.

To effectively measure cycle time, a tracking sheet was devised to be used with all optical heads in production. Figure 11 is an exact replica of the sheet used for tracking cycle time.

Optical Head Throughput Tracking Form

CES ○ Upgrade ○ Serial # ____________

2000 KOH ☐ ☐ 2100 KOH

CD KOH ☐ ☐ Prototype

PARTS SORT:	Begin	Date	Time	Initial
	End	Date	Time	Initial
STATION 1:	Begin	Date	Time	Initial
	End	Date	Time	Initial
STATION 2:	Begin	Date	Time	Initial
	End	Date	Time	Initial
STATION 3:	Begin	Date	Time	Initial
	End	Date	Time	Initial
STATION 4:	Begin	Date	Time	Initial
(CD Spin Test)	End	Date	Time	Initial
RELEASE:		Date	Time	Initial

COMMENTS: ____

____

The top of the sheet allows the user to indicate the optical head type and its classification as a CESD (field replacement) head or an upgrade head. CESD and upgrade heads require more testing since they do not receive testing time in the final product test. Instead they are used as spare parts to replace or upgrade units in the field. Since production methods for all three optical heads use station numbers, the same sheet can be used for all three products. Begin and End times are recorded to note actual time in process and idle time (time between station where no value is being added). The release date and time, with comments, are provided at the bottom of the tracking sheet.

To facilitate cycle time tracking, an automated database was developed for the assembly operators to use. Using Microsoft Excel[13] macros in a spreadsheet, operators were able to type in data directly from the Optical Head Throughput Tracking Form. This in turn automatically updated the spreadsheet and graphs. Operators then could print the graphs out to obtain detailed information on cycle time within the factory. Figure 12 shows the screen assembly operators see for updating information. Head serial number with Begin and End times for each station are recorded. Not shown are active buttons on the screen which update, save, print, and display graphs. Cycle time graphs presented in this chapter are representative outputs from the automated database.

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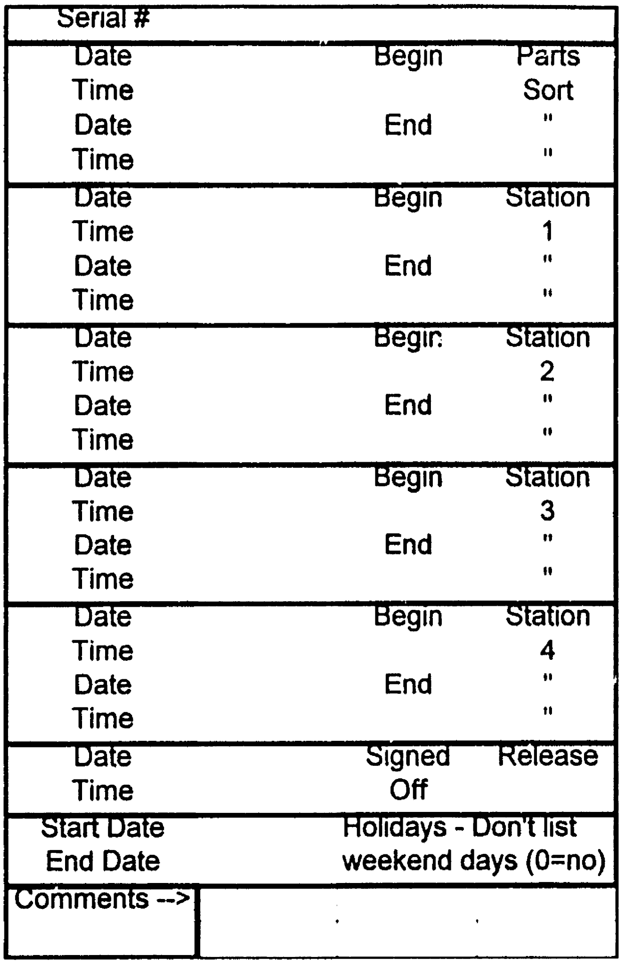
[13] Microsoft and Excel are trademarks of Microsoft Corporation.



Serial #		
Date	Begin	Parts
Time		Sort
Date	End	"
Time		"
Date	Begin	Station
Time		1
Date	End	"
Time		"
Date	Begin	Station
Time		2
Date	End	"
Time		"
Date	Begin	Station
Time		3
Date	End	"
Time		"
Date	Begin	Station
Time		4
Date	End	"
Time		"
Date	Signed	Release
Time	Off	
Start Date	Holidays - Don't list	
End Date	weekend days (0=no)	
Comments -->		

Figure 12: Data Entry Screen for Automated Database

The software on Excel was developed to provide detailed information to operators so improvements could be made to the production process. Figures 13-15 illustrate typical graphs for the KOH CD cycle time. A discussion follows that includes the reasons, results, and usefulness of each graph.

Figures 13 and 14 (as of 11/30/95) provide historical cycle time information for KOH CD production cycle time[14]. Figure 15 illustrates the cycle time in days for each optical head, denoted by serial number, for the last 100 (rolling) optical heads produced. The most recent are on the righthand side of the graph. The data is presented in the order the heads are completed. Figure 14 shows the same data except the data is presented in the order

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[14] Cycle time data in this chapter has been altered to hide actual data.

the heads started. Since heads do not necessarily start and finish in the same order, it was important to provide both graphs. The "order of completion" graph allowed heads with exceptionally long cycle times (usually a result of excess rework) to be weighted equally with other heads. The "in order started" graph pushes such products unfairly to the left of the graph once they come off the line. For example, an optical head with many production problems could feasibly sit in an engineer's lab for a few months. Once it is finally completed, so many heads may have been produced that it will not even appear on the "in order started" graph. This does not provide representative data of actual cycle time, since poor performers are always pushed to the left of the graph. Therefore, Figure 14 is used to provide trend data for the order heads begin production, while ***all*** other graphs display the order in which heads complete production.

Looking at Figure 13, the Kanban production system was introduced sometime near optical head serial number 640. Note that cycle time does not drop immediately, in fact it increases slightly. This was a result of operators learning how to use the system properly. Because the Kanban system made it much more difficult to work around or hide problems, operators initially tended to "add a few extra units in" for fear production would stop. Also, process problems decreased throughput, increasing cycle time. This continued for about two months, until the operators finally shut the line down for over one week. This production stoppage forced engineering to address some of the process issues inherent in the factory. The increased cycle time before the large drop is the result of product sitting idle in process while engineering fixed process problems. Once the problems were found, production resumed and cycle time dropped dramatically. Figure 14 shows this same data with the order the heads began production.

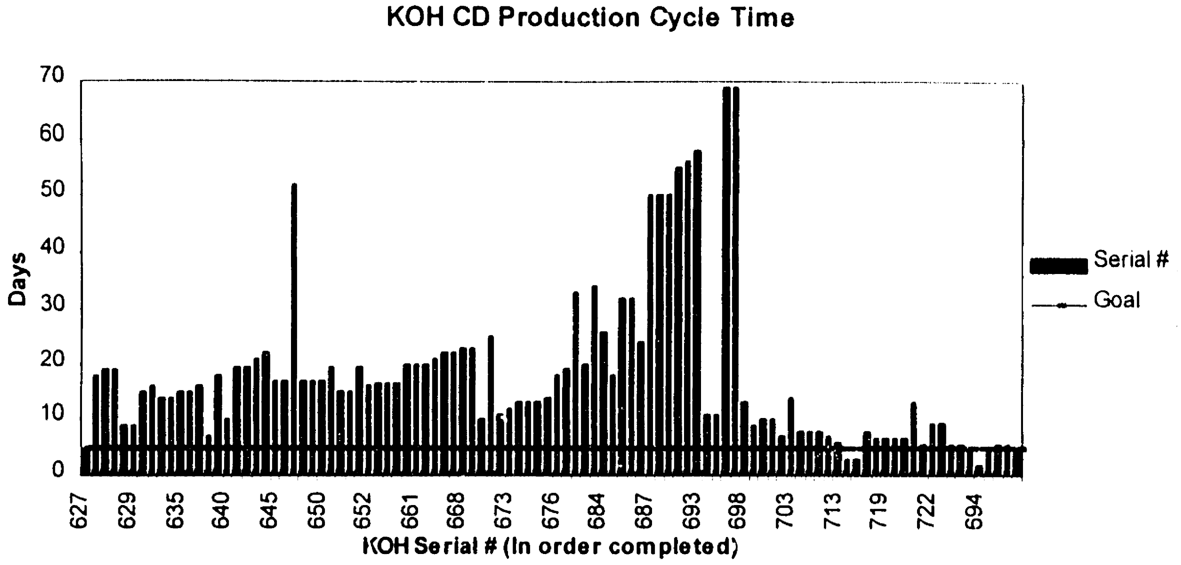

Figure 13: KOH CD Production Cycle Time

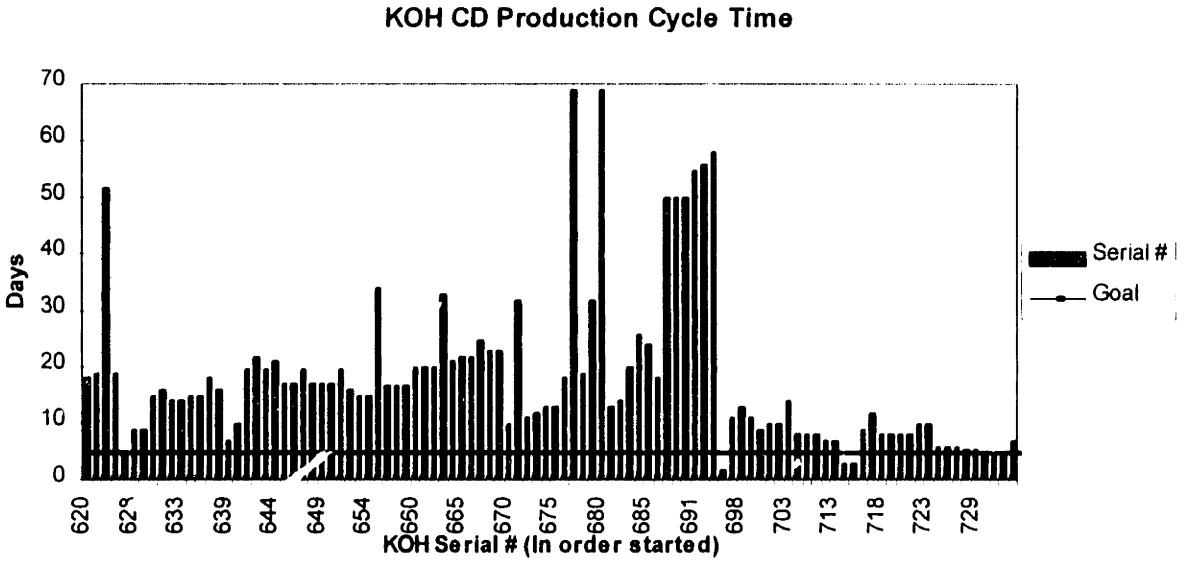

Figure 14: KOH CD Production Cycle Time

The cyclical rising trends in the "order completed" graph are a result of part releases by the vault. During the line shutdown, all parts were moved to the floor so these slowly rising trends no longer appear. Figure 15 shows the average cycle time, in days, for the last 20 optical heads produced. This is a rolling average which the operators can use to determine their cycle time. In June of 1995, the cycle time for the KOH CD was twenty four days. Figure 15 illustrates this cycle time had dropped to roughly six days, a 75% reduction in cycle time.

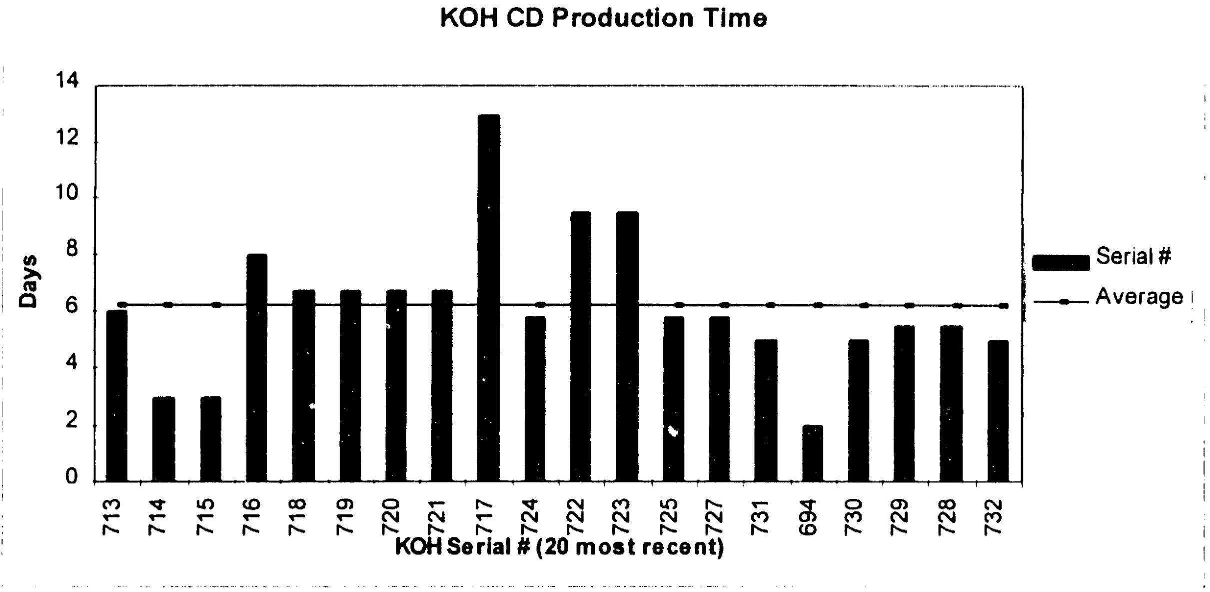

Figure 15: Average Cycle Time for KOH CD on 11/30/95

Figures 16-18 illustrate the same graphs dated almost three weeks later. It is clear that the process improvement made by engineering and the team's operation of the Kanban system provided a lasting improvement. The slight increase near the end was the result of Station 2 breaking down the last week data was collected. The station was repaired during that week. Figure 18 (12/19/95 20 rolling average) illustrates the average increased about two days because of this failure in Station 2. Operators were working hard to reduce the cycle time below six days once Station 2 was repaired. Clearly, the operators did not panic and violate the Kanban rules during these crises. This was due to the preparation and practice the team received prior to the production line shut down.

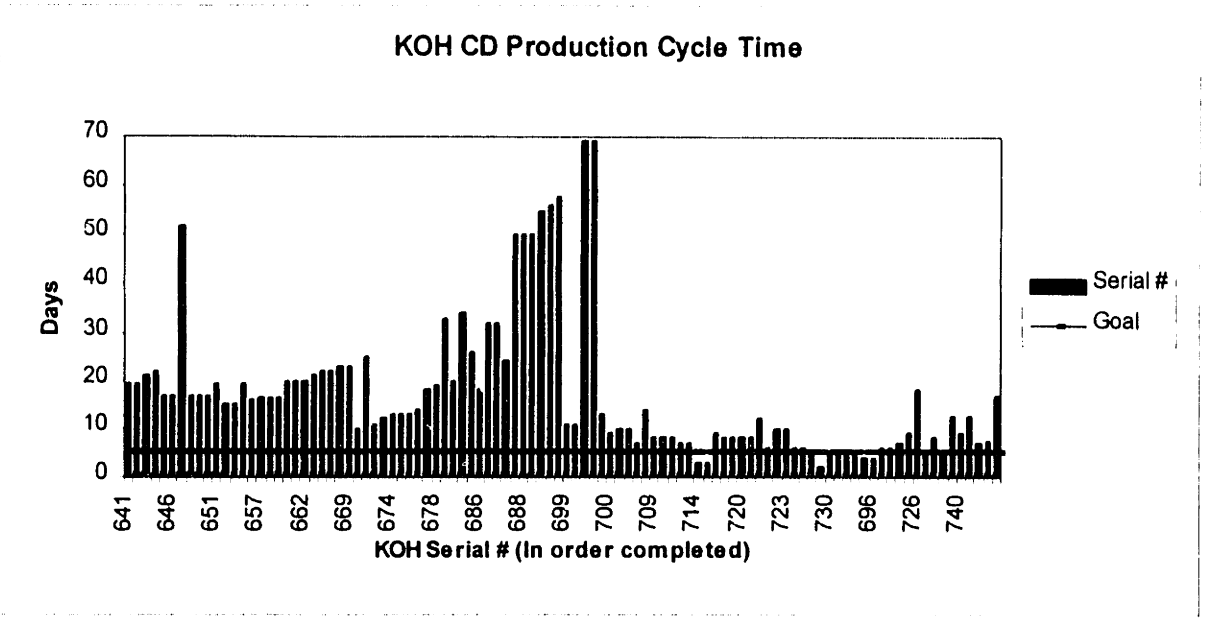

Figure 16: KOH CD Production Cycle Time, As of 12/19/95

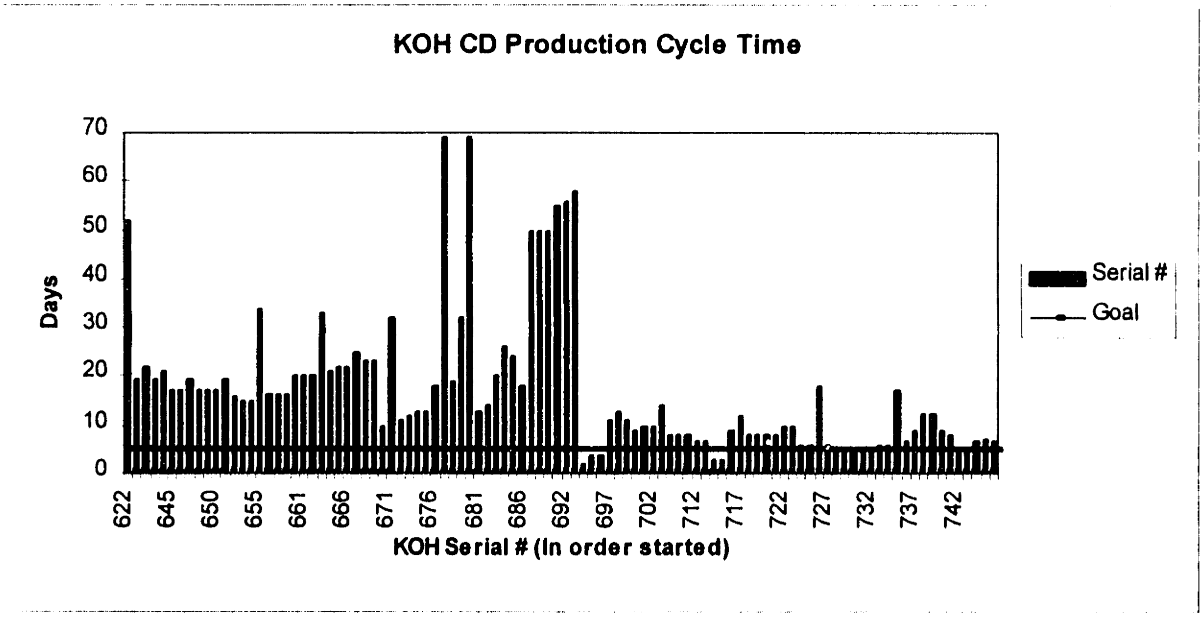

Figure 17: KOH CD Production Cycle Time, As of 12/19/95

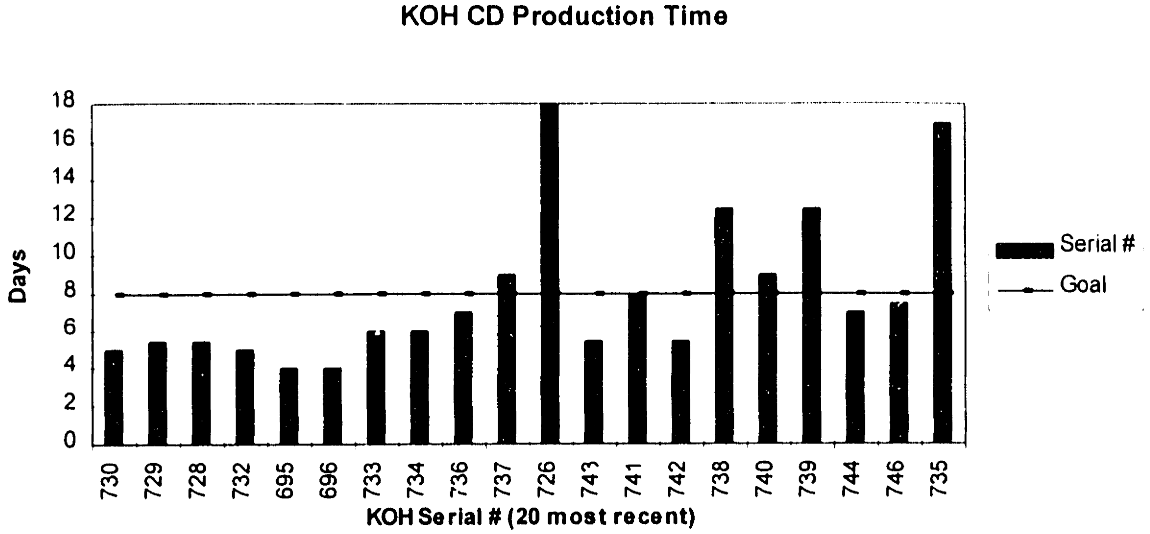

Figure 18: KOH CD Average Cycle Time on 12/19/95

The team attempted to maximize the use of the collected data for understanding the production system better. The Excel spreadsheet is programmed to calculate actual cycle time in hours for each station. The program subtracts out non-work hours (overnight), weekend hours, and holidays. Unattended process times are then added to each step if needed beyond normal work hours. For example, if a unit begins Station 1 at 2 PM on Friday afternoon and finishes at 7 AM on Monday morning, the total cycle time for the station is calculated as follows. The program assumes an 8.5 hour workday from 6:30 AM to 3:00 PM. One hour of cycle time is added on Friday afternoon, a half hour on Monday morning, and 12 hours of adhesive curing overnight. The overall cycle time would be calculated as 13.5 hours for the unit in Station 1.

Figure 19 shows the individual cycle times of the last 20 CD heads for Station 1 in hours. This data was taken on 12/19/95. The average cycle time for the station is also represented. The units with longer cycle times were caused by alignment errors in the optics. This required separation of the optical stack from the casing, resetting, curing, and an additional alignment check.

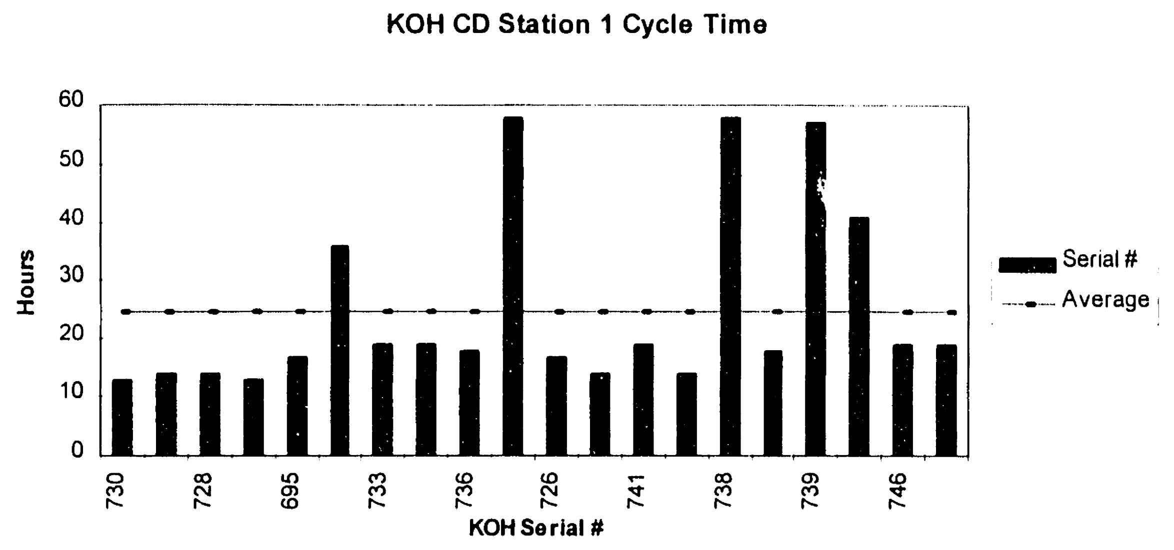

Figure 19: KOH CD Station 1 Cycle Time, Most Recent 20 Moving Average

Figure 20 illustrates the same data for Station 2. Note the increased cycle time on the last units to move through the station as the station breaks down. Additionally, since the operators had removed the overnight cure from Station 2 to improve cycle time, it was possible to attain low hourly production times for some of the units.

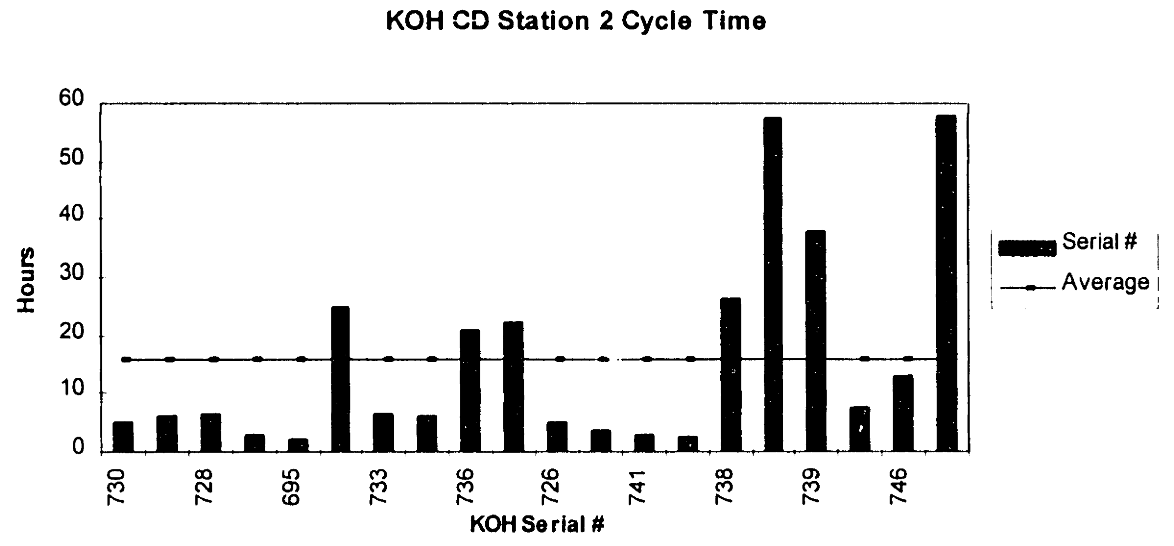

Figure 20: KOH CD Station 2 Cycle Time, Most Recent 20 Moving Average

Figure 21 illustrates the cycle time for Station 3. Once again, a few CD heads had long cycle times through this station as problems (in the heads) were discovered. The spikes are a result of poor collimation from Station 2. This was caused as Station 2 began to fail. It is believed some of these heads carried the problems to Station 3. An overnight cure time is expected to be shown in one of these graphs but does not appear. Further investigation revealed that the operators had determined cycle time could be further reduced if the CD heads were sent to the 6X-writer and allowed to cure between production lines. Because the heads were shipped in the afternoon by the KOH production line and used the next morning by the 6X-writer production line, it was not necessary to keep them an extra day in KOH. This resulted in one day's reduction of cycle time.

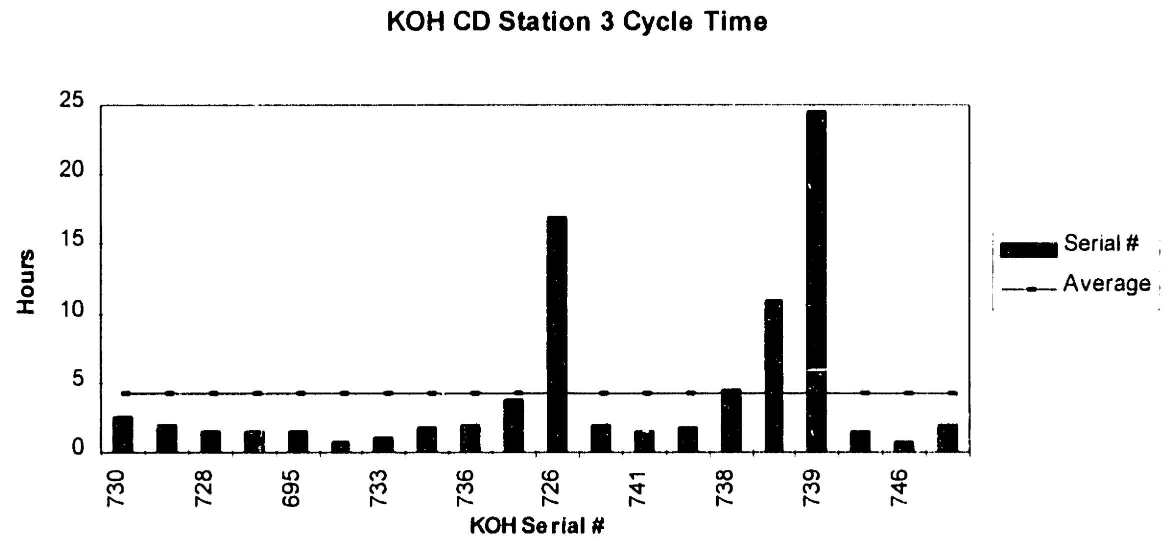

Figure 21: KOH CD Station 3 Cycle Time, Most Recent 20 Moving Average

Figure 22[15] provides stacked bar charts for production of Stations 1-4, parts sort, and the final release (parts sort and final release were negligible since nonvalue added processes were removed). Station 4 data represents the CD spin stand. This graph allowed the

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[15] The stacked bar chart was not an ideal method for representing the data. It is difficult to see trends in the data.

operators to determine which process steps required the most time, and work at reducing such process times. Once again, note the increase in Station 2's cycle time relative the other stations when Station 2 failed.

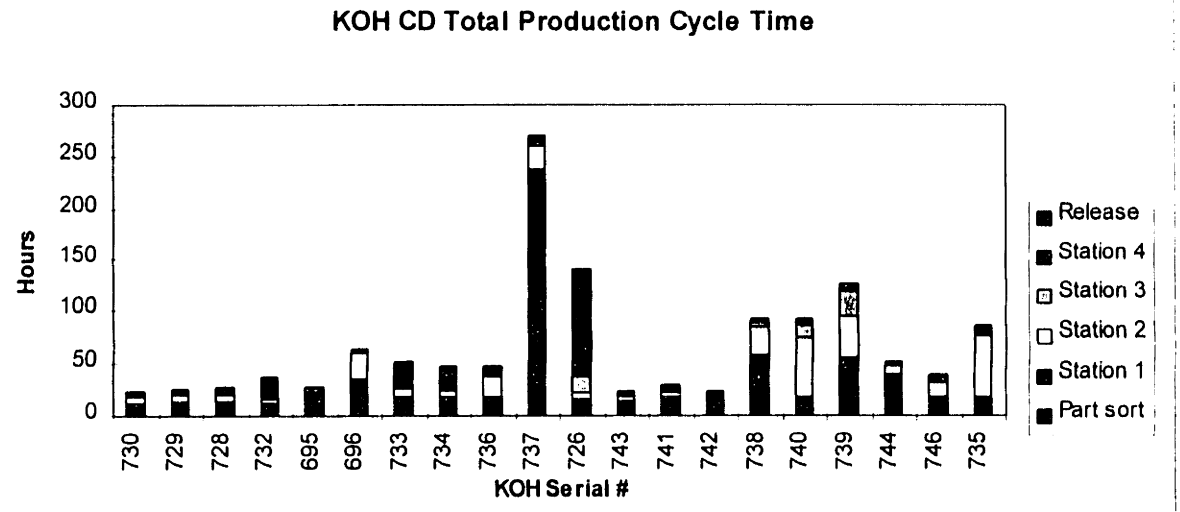

Figure 22: KOH CD Total Production Cycle Time, Stacked Bar Chart

Since operators tracked the **Begin** and **End** times of each station, it was possible to determine the amount of time products sat idle (between station) on the production line. Much of this is due to Kanban sizing, demand fluctuations, process problems, and parts shortages. Figure 23-a shows a stacked bar chart for idle time between stations. Once again, the increase between Station 1 and Station 2 is apparent as heads wait for the Station 2 to be repaired. Figure 23-b displays this same information in an easier to read form (grouped bar chart[16]). The cycle time data entry sheet automatically outputs idle cycle time as shown in Figure 23-a. The difficulty of reading such a chart prompted Figure 23-b, a representation of the same data in sequential bar chart form.

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[16] Terminology and graphing idea from: Cleveland, William. Elements of Graphing Data. Wadsworth Advanced Books & Software. Monterey. 1985

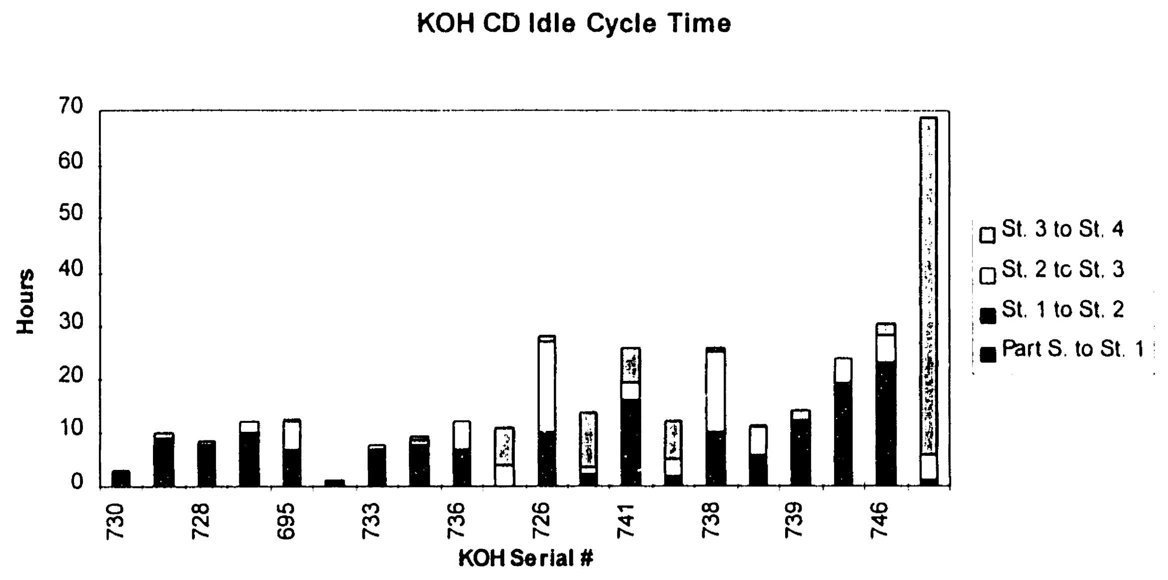

Figure 23-a: KOH CD Idle Cycle Time, Stacked Bar Chart

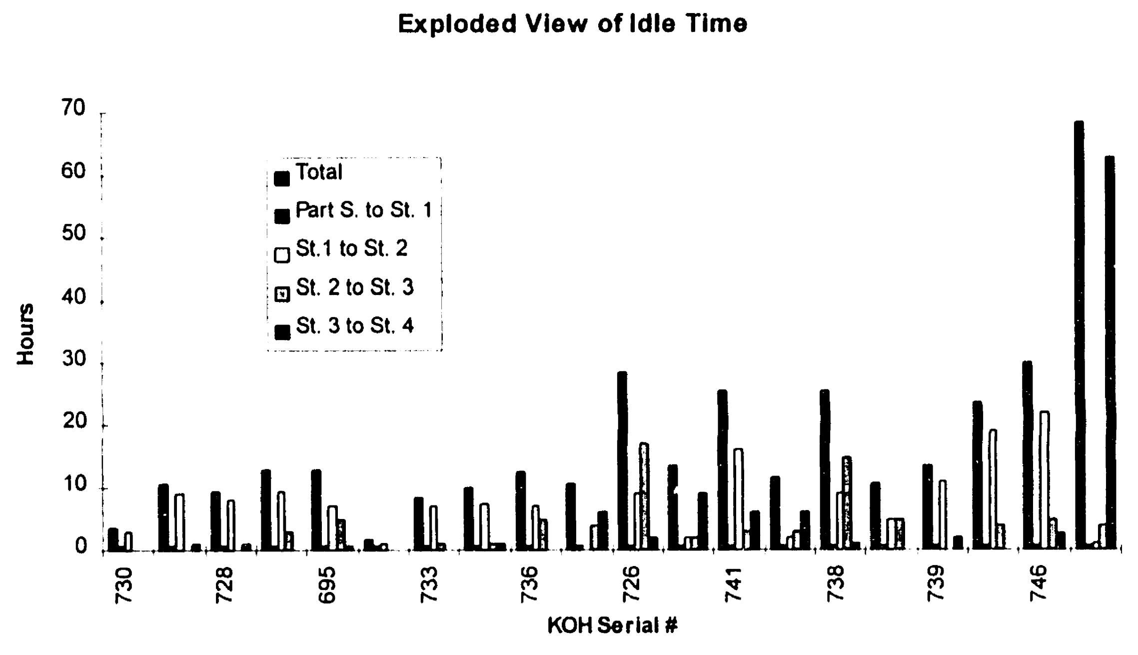

Figure 23-b: KOH CD Idle Cycle Time, Grouped Bar Chart

While these graphs are all generated and printed at the same time, the total cycle time production graphs in days (Figures 14-16) are the most relevant. They track actual cycle time in days as seen by the customer. The graphs used to calculate individual cycle time at each station did not provide the accuracy of information desired. If an operator worked overtime, the data could be skewed. Additionally, if an operator went to lunch and left a unit in process, time was counted against the unit.

One of the most difficult aspects of measuring specific station cycle times was caused by the Kanban system. Station 2 is used as an example. There are two main process steps in Station 2, collimation and actuator installation. It was common that operators would run all of the heads through collimation first. This caused units to accumulate "in-process" cycle time even though only one was going though at a time. Once the first head went through collimation, it sat idle accumulating in-process cycle time as the second and third heads were collimated. The third head to be collimated was ***not*** collecting "in-process" cycle time while the first two heads were collimated however! Additionally, there was no guarantee that the heads had actuators installed in the same order they were collimated. In other words, it was not a true FIFO (first in first out) system. Sometimes it was LIFO, other times FIFO, and sometimes neither depending on the person and circumstances. This resulted in inaccurate data.

Tracking ***station*** cycle times in a low-volume environment was difficult to accomplish. Many improvements are needed before the data is valuable. Additionally, interpretation of the graphs is not easy. The reader can clearly see that if no information was known about Station 2, it would have been difficult to analyze the data in Figures 17-21 (station graphs).

Perhaps there is a limit to the amount of data collection possible in certain production environments. Acquiring accurate station cycle time data (which involves more detailed data collection) may not be possible in this environment. If the data collection becomes a significant part of the production time, accurate data is obtained at the cost of adding a nonvalue added process. Perhaps 25% of a station's cycle time could be the result of data collection. This is analogous to measuring the temperature of water. Placing a thermometer in a swimming pool does not change the temperature of the water. Trying to measure the temperature of a drop of water with a thermometer can lead to erroneous results, since the thermometer's temperature will most likely alter the water droplet's. Operators suggested installing bar code readers to improve data collection; however, this was not accomplished by December.

On the other hand, the overall production cycle time graphs were very valuable. They provided accurate data since the **begin** and **end** times were accurately recorded for each unit. Since cycle time was tracked in days and not hours, it was not necessary to develop elaborate formulas for determining cycle time.

Appendix B shows the same data for the KOH 2000. Because less units were produced in the Kanban system, dramatic reductions in cycle time had not occurred. It appears that at least 50 units of production are needed (based on the KOH CD data) in the Kanban environment to begin to uncover some of the hidden problems. The KOH 2000 had not reached this critical mass yet, although improvements were beginning to show. In June of 1995, overall cycle time for the KOH 2000 was about 38 days. This was reduced to only 32 days by December, however the last five heads recorded showed an average cycle time slightly over 10 days.

Clearly, the use of the Kanban system in a low-volume environment was extremely effective. Cycle time was reduced substantially for the KOH CD and hidden problems were discovered.

6.3 Production Planning - Better Optimized

Before the Kanban system was installed, operators looked at weekly schedules generated by the MRP-II system, and batch heads based on the existing tooling capacity. This occurred at Station 1, where optical stack mount and pointing occurred. Station 1 thus set the batch sizing for the factory by default. Since the operators did not have production planning software to optimize factory throughput, they would usually begin production in the following manner.

With eight tools for curing optical stacks into casings, they would use all eight for one product type. For example, if the weekly schedule demanded eight KOH CDs and six KOH 2000s, the operators produced only KOH CDs on the first day. On the second day, they would lay up KOH 2000s. This created batches of eight and six KOH CD and KOH 2000s respectively, which were not optimal for factory production. This also created additional work-in-process and created moving bottlenecks. The bottleneck followed the huge batch through the factory, since no station had the capacity the run the entire batch through in one day.

The Kanban system alleviated production scheduling problems, and eventually decreased cycle time through improved production scheduling. Products were produced as needed, not as scheduled. Instead of stuffing the existing tooling to capacity with one product type, the tooling was used only as a means to fill a Kanban tray. For example, if the Kanban "HOLEs" were empty for KOH CD and KOH 2000 heads, three KOH CD and two KOH 2000 heads were produced through Station 1. This required the use of five, not all, tooling fixtures for curing optical stacks. When yield problems arose, operators had the ability to increase the number of stacks produced. For example, four instead of three KOH CDs might be processed. This allowed for one failure, which would be reworked the next time KOH CDs were needed. If all four KOH CD optical stacks passed without failure, then one sat idle until needed, collecting cycle time. The operators were very cognizant of the fact that perfect yields reduced the need for curing additional optical stacks.

Since the tooling was used to produce different products simultaneously, it was important to be able to distinguish one product from another. KOH CD and KOH 2000 used different optical coatings on the stacks, not easily identifiable by the human eye. One of the operators cleverly devised a labeling system using color coded magnets to identify product type to minimize confusion.

One of the greatest benefits the Kanban system provided surprised everyone on the team. Before the system was installed, team members argued about the manner in which optical stacks needed to be processed through Station 1. Since some operators focused their production on specific product types (KOH CD or KOH 2000), they would complain when their product was not produced in Station 1, since this meant work for them would be delayed. The Kanban system eliminated all of these problems. Team members quarreling with one another was drastically reduced, providing a better work environment for everyone.

6.4 Variability - Still High, Problems Exposed

With the Kanban system running, variability in process steps became highly visible quickly. A large amount of work-in-process was no longer around to hide problem areas. Unfortunately, the Kanban system does not provide a systematic way to tackle these problems. Line shut downs obviously became priority, though the cost of these shut downs were not documented. Activity based costing would provide engineering a systematic way to tackle these problems. At the time of this thesis writing, variability in the system was still high. Although some problems had been identified and corrected, reducing cycle time significantly in some cases, there were still many more problems needing attention. In fact, it appeared that new problems surfaced on a weekly basis.

Two months after the Kanban system was installed, the team began to better understand its use in identifying problems. For example, it became clear that if process times could be reduced, then problems causing poor yield could more quickly be identified. The most intriguing aspect of the Kanban system was the feedback loop built in which forced continuous improvement. Once engineering solved problems highlighted by the system, the team identified ways to reduce Kanban sizes, which reduced cycle time. This, in turn, highlighted more process issues, creating a greater need for engineering. As engineering solved these new problems, they allowed operators to identify more Kanban size reduction opportunities. This underlying system is shown in Figure 24. Unfortunately, the first iteration of this loop required approximately three to four months, so there is little data to illustrate Kanban sizing reductions. One thing is clear, this loop for continuous improvement can not exist without a production team constantly identifying new ways to reduce Kanban sizes. Training operators with these skills is crucial, since production engineers may not have the time needed to constantly evaluate the production environment.

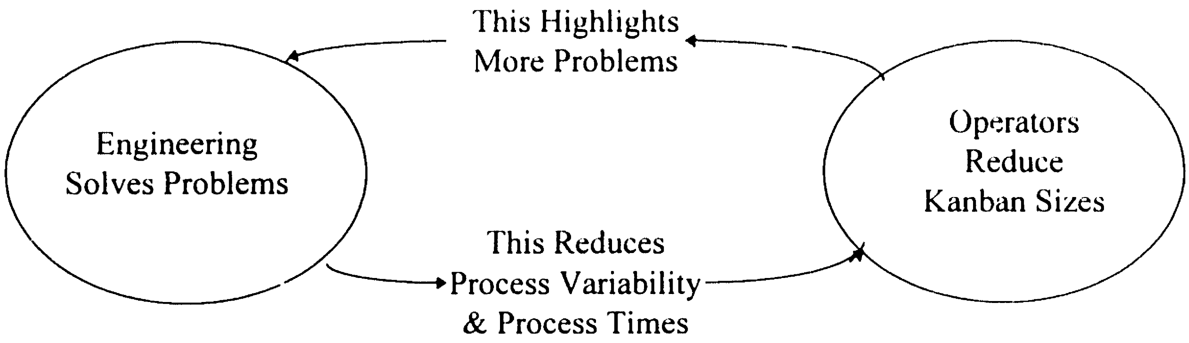

Figure 24: Continuous Improvement Feedback Loop

6.5 Cost of Poor Quality Still Unknown

The Kanban system does not measure the cost of poor quality. It only highlights high variability in the system, it does not determine the cost of this variability. The Kanban system does show where process times need to be reduced, but does not prioritize which process steps should be tackled first.

6.6 Cost of KOH too High

With over 70% of the optical head costs determined by components from suppliers, the reduction in work-in-process did not provide substantial savings on optical head production. While work-in-process decreased by over 50%, carrying cost were reduced by the same amount, however, these cost reductions were extremely small when compared with total product cost. Observations revealed that a majority of possible cost reductions come from component costs, so subsequent chapters in this thesis provide a discussion for attacking such costs. Using Kanbans with suppliers may reduce such component costs significantly, but this is not guaranteed since set-up costs may require large lot runs when compared with annual demand for a component.

6.7 Comparison with Kanban at Boeing Aircraft

The results presented in this thesis were compared with the research of Arthur J. Raymond[17]. Raymond found that pull production (Kanban) works well in low-volume environments with the exception of large structure production and purchased components. This thesis arrives at the same conclusion. Optical head production, which is a batch flow process for small products, seemed to work well in the Kanban environment.

Additionally, the purchase model discussed later in this thesis concludes that optimal purchasing policies do not necessarily correlate with multiple or just-in-time deliveries. Raymond's research states there is a low applicability to using Kanbans with suppliers for low volume, supporting this finding.

Finally, Raymond found that maintaining a flexible work force was difficult in a low-volume Kanban environment. This was reinforced at Kodak, where cross training usually required months for learning one station. It was difficult to remain current in all process steps without working in the factory for a considerable amount of time.

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[17] Raymond, Arthur. Applicability of Toyota Production System to Commercial Airplane Manufacturing. MIT, 1992.

7. Purchasing Model

7.1 Purpose of Model

There is a current trend in American business to reduce supplier lead times, increase inventory turns, and receive Just-In-Time (JIT) shipments from suppliers. Most of the research conducted to date focuses on how high-volume manufacturing units can use these concepts to reduce overall costs. Low-volume manufacturing units, with no common research to support otherwise, have tended to focus their efforts on these same goals. There is no certainty that increasing inventory turns or receiving shipments just-in-time reduce overall costs in a low volume manufacturing environment.

The purchasing model in this thesis was developed to ascertain the affects (costs) of the current buying strategy at Kodak's Optical Storage business unit, and compare them with the costs the model outputs based on a number of input parameters. These input parameters (except shipping charges - UPS, etc.) are utilized to determine an optimal buying strategy based on supplier volume quotes and expected demand. It is believed that the current buying strategy in use at Kodak was developed for higher volume manufacturing processes. With higher volume products rightly receiving more attention by management, the lower volume products are left out. Therefore, low-volume product lines succumb to inefficient buying practices for their expected volumes by following high-volume practices because there is no alternative. With over 70% of costs in the Optical Storage business unit associated with components from suppliers, these inefficient buying strategies are thought to have significant ramifications on the unit cost of the product. This model will help to determine the validity of the above claim.

7.2 Current Procurement Policies at Kodak

Kodak currently uses an ABC policy for determining volumes and quantities for components purchases from suppliers. "A" type components are the most expensive and include components such as circuit boards and motors. "C" type components are the least expensive components, such as screws and fasteners. When a new component is bid on by a supplier, the expected annual demand is used with the supplier quote to determine its classification. Once the component classification is determined, the buyer then sets a delivery schedule with a supplier based on the supplier's capabilities and the classification policy. The following guidelines are followed when possible:

- "A" type part: Should have no more than four to six weeks of inventory on hand at any given time.
- "B" type part: Should have no more than nine to ten weeks of inventory on hand at any given time.
- "C" type part: Should have no more than six months of inventory on hand at any given time.

7.3 Strategic Issues

Because the Purchasing Model developed helps to determine the optimal buying strategy by minimizing cost, it is important to look at other factors which may impact the organization as well. Since the following issues can effect the performance of the business significantly, it is important not to let current unit cost of a purchased component be the sole deciding factor when buying parts. Reducing lead time may increase costs in the short run, but may reduce overall costs in the long run. Since many costs are hidden and difficult to determine precisely, users of the purchasing model must use good judgment when buying parts. The following strategic issues are difficult to incorporate into the model, yet have significant impacts on overall costs in product life cycles.

7.3.1 Inventory Amounts/Turns

In the Optical Storage business unit at Kodak, there was an effort to reduce overall inventory and to increase annual inventory turns. Although this metric is easy to measure and on the surface appears to follow sound judgment, the materials organization within Kodak had no problem striving to improve this metric. Does this tie in well to optimizing components purchasing for a low-volume environment?

Reduced inventory certainly lowers holding or carrying charges. However, there was a concern that the resultant increase in materials costs (due to lower volume lot size buying) did not offset the savings in inventory costs. Additionally, increased inventory turns require employees to constantly handle incoming components shipments. With a low-volume environment, there was concern that the fixed costs associated with receiving a shipment could not sufficiently be spread over the low number of parts in each shipment, thus substantially increasing the cost per unit for each part.

7.3.2 Lead Time

Supplier lead time reductions benefit customers in a number of ways. First, they increase flexibility within the supply chain, so changing markets can be met more rapidly. Secondly, they reduce the amount of inventory in the supply chain which ultimately reduces carrying costs. Third, the flexibility allows for problems to be identified earlier in a product's life cycle, allowing suppliers to react to quality problems more quickly.

7.3.3 Critical Components

One of the most difficult issues low-volume manufacturers face concerns sole sourced critical components. Since significant power for low-volume manufacturers lies with suppliers, supplier relations are more difficult to manage. Low-volume manufacturers are generally not large customers for suppliers. This makes forcing a supplier to adhere to strict quality standards and delivery schedules difficult. Suppliers that solely supply critical components have significant power over their low-volume customer!

Suppliers can use their power over low-volume customers (i.e. Kodak Optical Storage business unit) in a number of ways. They can increase component costs because the customer has little choice (in many cases) of changing suppliers. Specially engineered critical components such as mechanical parts, lasers, and actuators are not easily switched to alternative suppliers. In a low-volume environment, sourcing such components to more than one supplier is usually cost prohibitive, since setup costs cannot be spread over a substantial volume.

Even if the sole supplier does not exercise its power, risk to the low-volume manufacturer is still high. The low-volume manufacturer is at the mercy of a the supplier who has quality and/or delivery problems it cannot easily correct. Additionally, if the supplier decides to no longer manufacture the part, low-volume manufacturers are required to perform a lifetime buy of the part, find another supplier, or manufacture the part themselves.

With thousands of parts needed to manufacture optical storage products, it is highly likely that many of these issues will occur on more than one part during the life of the product. In just one sixth month time period in 1995, three parts were discontinued by suppliers, causing Kodak to perform lifetime buys of these parts.

7.3.4 Moving Inventory to suppliers

Many suppliers are willing to hold inventory so Kodak inventory metrics can be met. Is this good? Some say it allows the supplier to monitor demand, and build accordingly. This could come at the cost of higher delivery charges, or late deliveries. When obtaining supplier quotes, buyers should work with suppliers to reduce overall inventory in the supply chain while monitoring other costs. Both the supplier and customer must consider all costs, delivery, setup, shipping, etc. to minimize overall costs. The purchasing model attempts to achieve this by considering a number of input parameters.

For example, it does not make sense to ship one screw every day, because shipping and handling costs will dominate the cost structure. On the other hand, it may be sensible to ship large frames daily, since they are expensive and require a large amount of room to store.

7.4 Development of Model

The Purchasing Model was developed based on the needs of the customer. The customers, in this case, were Kodak Materials Management personnel. Interviews were conducted that provided the input variables the model needed. Initially, the model was designed to output one optimal buying point. As the complexity of the output data increased, it was determined that the model's output needed to be more flexible. To meet this need, the model outputs two graphs and specific data.

The first graph is a surface plot, which plots the Quantity of parts Purchased (per order), and the number of Deliveries versus the Unit Cost. This graph shows the relationship between quantity and deliveries, so an optimum can be obtained. The second graph plots Quantity Purchased and Annual Demand versus Unit Cost to show the demand sensitivity at the optimal buying point. Perhaps the optimal point is highly demand sensitive, where a slight increase in unit cost can reduce the sensitivity risk significantly. Finally, the model outputs numeric values of best lot size, order quantity, delivery schedule, and provides a cost comparison between the optimal and current buying strategies.

The model also allows for multiple deliveries on one purchase order. In other words, the model calculates not only the frequency with which an order is placed, but also the number of deliveries for each order. Additionally, the model assumes Kodak pays for each delivery upon receipt. Multiple deliveries on a purchase order require a separate payment for each delivery, equivalent to the unit cost of one component[18] multiplied by the delivery lot size. An example output might show placing an order once a year with monthly deliveries. This represents a committal from the buyer (Kodak) of one year's worth of components delivered (and paid) monthly. If the annual commitment is 144 units, the monthly delivery amount is 144/12= 12 units per month, with Kodak only paying for those 12 units at the volume price generated by committing to 144 units overall.

7.4.1 Input Parameters

7.4.1.1 Part Number & Description

The first piece of information the user enters is the part number and description. This is for recordkeeping purposes so that when a printout report is generated, the part number and description reside with the graphical data.

7.4.1.2 Supplier Volume Quotes

Historical data and experience show that most (if not all) suppliers quote in a step function form. In other words, a supplier will quote different price breaks at specified volumes. This is usually done to provide an incentive for the purchaser to buy at a higher volume, where the price break occurs. A typical example is shown below in Table 2.

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[18] The unit cost of the component is determined by the quantity commitment between Kodak and the supplier, based on the order size, not delivery size.

Minimum Quantity	Maximum Quantity	Price/unit
50	99	$24.50
100	199	$18.75
200	499	$15.25
500	999	$12.00
1000	1999	$9.80
2000	-	$8.70

Table 2: Sample Supplier Volume/Price Quote

Table 2 clearly identifies price break points at 50, 100, 200, 500, 1000, and 2000 units purchased. As the quantity increases, the price per unit decreases as expected. For example, if Kodak purchases anywhere from 50 to 99 components on a purchase order, the unit price for each component is $24.50, regardless of the volume purchased within this range. Note that this piece price decreases when Kodak is willing to commit to 100 units on a purchase order, at $18.75 each. With a 100 unit commitment on a purchase order, Kodak is responsible for 100 x $18.75, or $1875.00. If only 99 units are committed to, the total cost of the order is 99 x $24.50, or $2425.50, $550.50 more than committing to 100 units. Thus, the supplier has created an incentive to purchase in higher volume.

The model was developed to allow for step function inputs similar to the one above. The user needs to only input the price breaks (minimum quantity values) and respective prices.

7.4.1.3 Safety Stock

Although carrying a safety stock does not have a direct impact on purchase quantities, it does have a significant impact on overall carrying costs. Since the "optimal" solution is to carry zero inventory as a buffer, the Safety Stock is not determined by the model. The user inputs this value based on expected risk, component history, supplier performance, etc. The model does take this value and include the carrying costs of safety stock in the unit costs displayed in the output. While this allows the model to continue to output useful cost information, it does not prohibit the buyers from maintaining safety stock, and monitoring its impact on overall costs.

7.4.1.4 Initial Stock

Many times, when a buyer is entering data into the model, the inventory on hand does not equal the safety stock when a new order is placed. Ideally, a new order would be placed when inventory levels fall to the safety stock level. Since the world is not ideal, this is usually not the case. Perhaps a supplier can only deliver at a certain time, or demand is fluctuating wildly. To counter this phenomenon, an Initial Stock variable is placed in the model. This allows the user to input the difference between actual stock and Safety Stock as the Initial Stock.

For example, if the actual stock on hand is 102 units, and the Safety Stock is set to 100 units, the Initial Stock is 2 units. Similarly, if the actual stock is 98 units with the same Safety Stock, the initial stock is -2 units.

If these two variables are combined in the model, why differentiate the two? Stock on hand is stock on hand, right? The buyers interviewed wanted the Safety Stock separated for simplicity. This allows a set Safety Stock to remain easy to see. Additionally, the level (value) of the Safety Stock is less likely to be altered accidentally by the user.

7.4.1.5 Set-up Costs per Order

The model allows the user to input set-up charges (fixed cost) for *each order placed.* This is not to be confused with one time *non-recurring engineering fees*, which are not entered into the model. These fees are amortized over the life of the product, regardless of the number and size of orders placed. While it effects the overall Unit Cost of the product, it has no impact on the optimal buying decision.

The model also assumes that a supplier will only perform the setup once *per order*. If there are multiple deliveries on the order, each requiring a set-up charge, this cost is placed in the *Costs per Delivery* input variable.

7.4.1.6 Delivery Costs

This input allows the user to separate fixed delivery costs from fixed order costs. For example, there may be administrative fees, shipping fees, and a set-up cost charged for each delivery.

7.4.1.7 Carrying/Holding Costs

In order to accurately account for moneys tied up in inventory, the user has the ability to enter the carrying/holding cost rate. This rate, in percent form, includes[19]:

1. The cost of providing space to store the items
2. Taxes
3. Insurance
4. Breakage, spoilage, deterioration
5. Obsolescence
6. Cost of capital or alternative investment

Typically, the last cost is the dominant factor in the holding cost rate, contributing about 75% to the overall rate. Kodak uses an annual holding cost rate of about 20% for

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[19] These items are taken from Nahmias, Steven. Production and Operations Analysis. Chapter 4.4.

equipment. For example, $100 worth of inventory held for a year costs Kodak 0.2 x $100 = $20. Of this $20, about 0.75 x $20 = $15 is the cost of capital.

Many companies include personnel costs in their holding cost rate. This is usually associated with the first item on the above list, the costs associated with storing and handling incoming components. In a low-volume manufacturing environment, these employee costs can be significant as a percentage of unit cost. For this reason, employee ordering and inspection costs are not included in the holding cost rate, but entered separately.

7.4.1.8 Order Time & Burden Rate

The amount of time a buyer or planner spends on the purchase order, including obtaining quotes and interfacing with the supplier, is recorded in the model. Additionally, the burden rate, or cost per hour of the employee is entered. The burden rate is fairly constant, but the ordering time can vary significantly from one order to the next. The burden rate normally includes an employees salary, benefits, office supplies, heating, air conditioning, etc. The salary and benefits could be separated from the other factors which contribute to the burden rate. This was not done because the model attempts to capture long term cost savings. In the long run, the number of employees can change as well as the space they occupy in a building. Furthermore, this portion of the costs is fairly small when compared to overall costs.

7.4.1.9 Inspection Time & Burden Rate

The inspection time and associated burden rate follow the same guidelines as the order time and burden rate above. The inspection time refers to the amount of time required to inspect *each delivery*. The model assumes receiving, inspecting, and storing incoming components is independent of delivery lot size. While this may seem incorrect on the surface, a close look at the receiving process indicates otherwise.

For many components, the inspection process is not a major contributor to time. Detailed inspections usually occur on the floor by factory operators who know the components well after they have been received. The initial receipt generally involves looking for obvious defects and storing the components in the proper location.

7.4.1.10 Maximum Allowable Buy

The maximum allowable buy has no affect on the output of the model. The only use it provides is an error warning if the optimal buy (in volume) is in excess of the annual demand multiplied by the maximum buy number of years. For example, the maximum buy may be set to 1 year by the user. If the model's optimum output is to buy 600 units when the annual demand is 400 units, more than one year's worth of supply is outputted. A warning is given to reduce the range of the graph to 400 units.

7.4.2 Mathematical Development

The development of the model required a clear understanding of the relationship between Kodak and its suppliers. The challenge was to create a model that accurately reflects various buying practices with the different suppliers. Since all suppliers cannot deliver components identically, flexibility was a key issue needed in the purchasing model. Through interviewing buyers in optical storage and looking at historical data from previous purchases, certain trends were noticed in buying practices. These trends are grouped below and separated for clarity.

7.4.2.1 One Shipment per Order

Many suppliers did not want to ship multiple deliveries for each purchase order received. These typically were suppliers of "C" item parts. These suppliers believed their low unit cost did not warrant multiple deliveries for each order.

There was also a number of suppliers which had high set-up costs for an order. These suppliers typically expected the Kodak buyer to determine any economic order quantity sizes and purchase accordingly, since the buyer has better information on expected demand. Thus, they delivered an entire order once produced, usually in one bulk shipment.

Finally, a few suppliers decided to no longer produce certain components. These suppliers required Kodak to perform a "one time buy" of these critical components. This buy was expected to last the entirety of the product's life, almost always in years. Thus the supplier no longer manufactured the product after this one time production of a component.

These three types of occurrences, while different in nature, mathematically yield the same end result. A one time delivery under a purchase order, carrying a large amount of inventory over the purchase order duration. Mathematically, determining the optimal buying strategy under this condition is easiest, since the number of deliveries is held constant to one. In the case of the one time buy, the model is used to determine the excessive cost incurred due to this *sub-optimal* purchase of components.

Thus, the model has to be capable of determining optimal buying strategies based on one delivery per purchase order. This is illustrated in Figure 25.

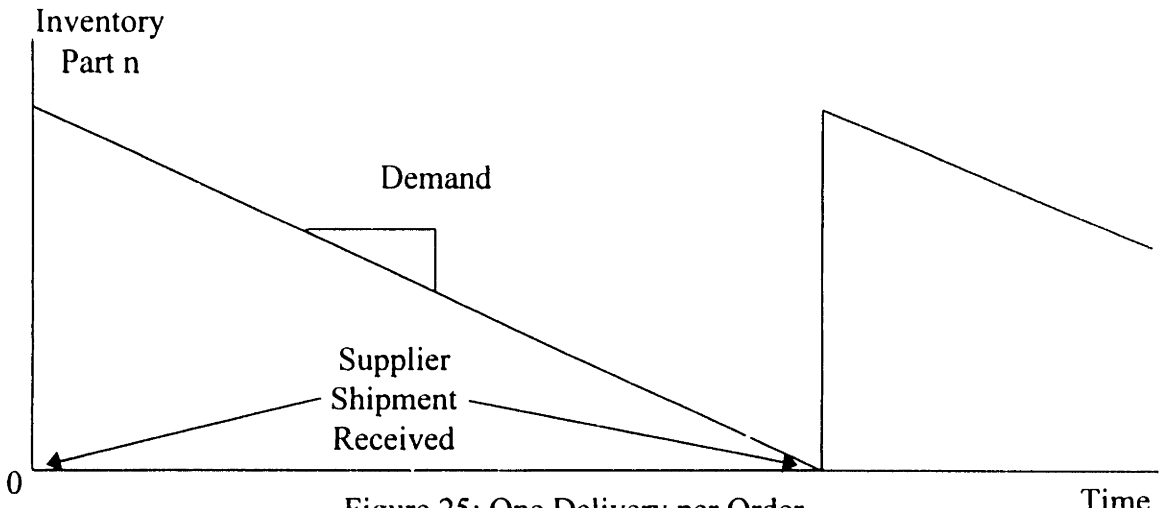

Figure 25: One Delivery per Order

7.4.2.2 Evenly Spaced Supplier Deliveries

Many suppliers agreed to provide multiple shipments on one purchase order. This allowed Kodak to maintain lower inventories, but added complexity to the model. The buyers not only wanted to know the size of a purchase order, but the frequency and number of deliveries for each order. The model needed to be capable of determining the best quantity and delivery schedule simultaneously.

With evenly spaced supplier shipments, there are three delivery scenarios the model must be capable of handling. These are all based on the difference between demand rate and incoming delivery schedules.

The first case, illustrated below in Figure 26, is the most straightforward. When demand rate and incoming delivery schedules are identical, on average, components are used at the rate they come into the factory from the supplier.

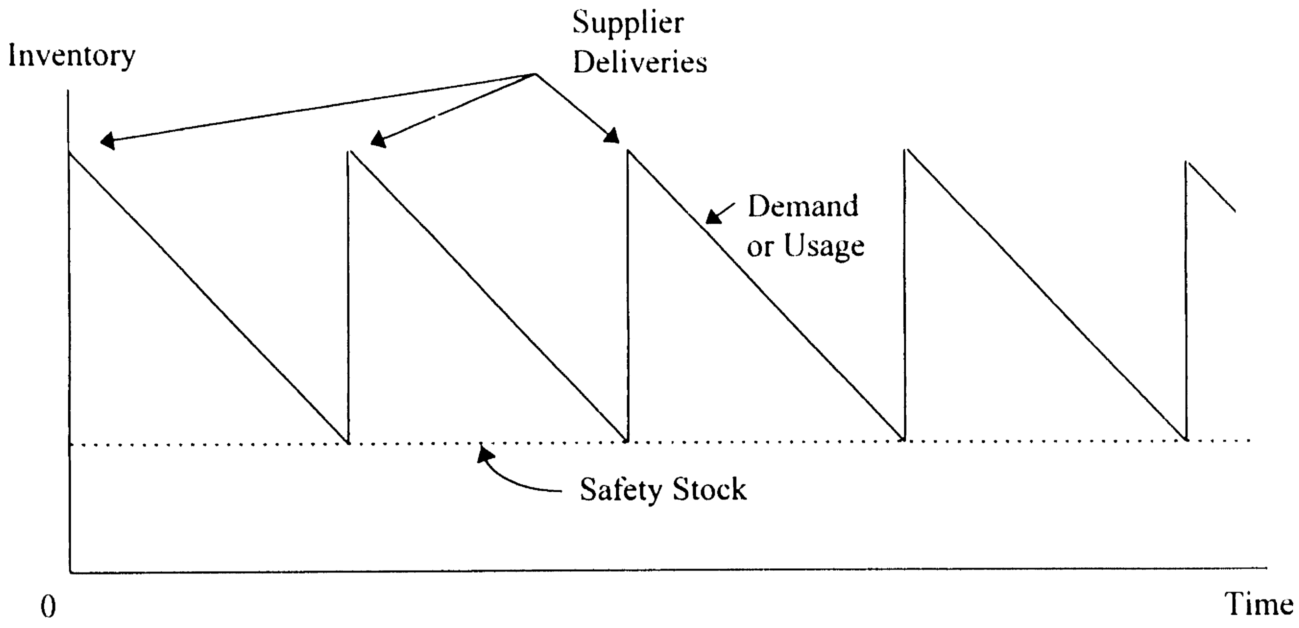

Figure 26: Multiple Deliveries per Order

The second case occurs when components are shipped to the factory more quickly than they are used, determined by the demand rate. In this case, the average inventory slowly builds up over the duration of the delivery schedule, until the deliveries cease. Then, the remaining inventory is used to completion or the desired safety stock level. This is represented below in Figure 27.

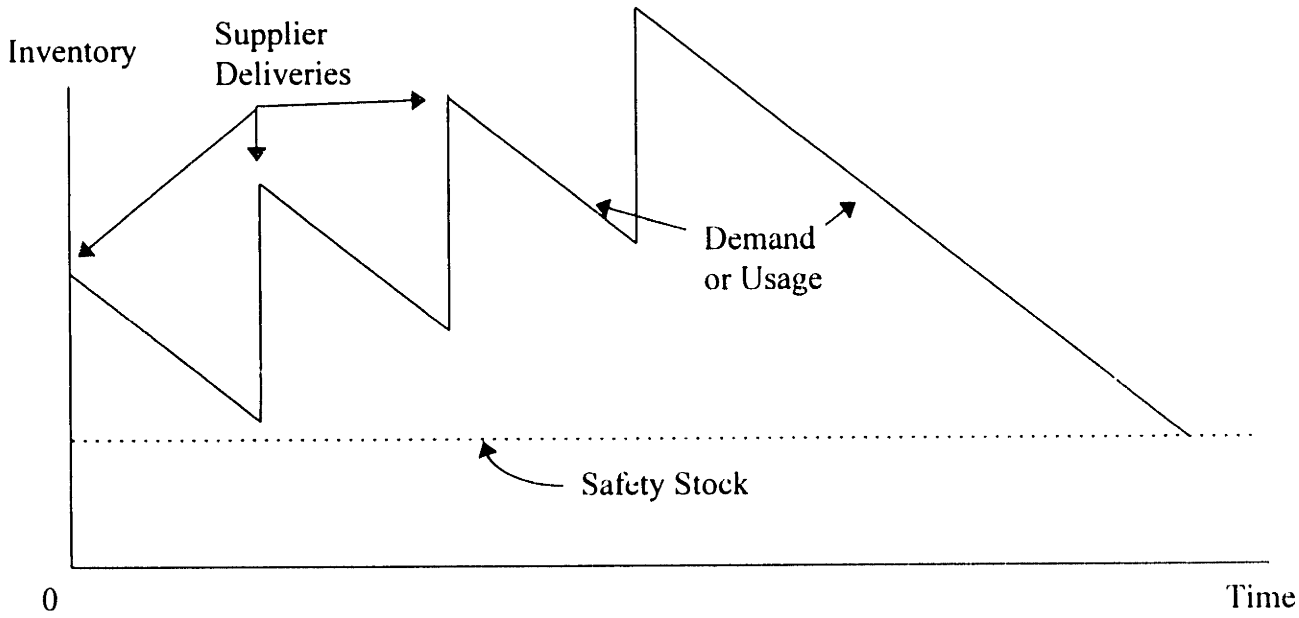

Figure 27: Supply Rate is Greater than Demand Rate

The third and final case occurs when demand outstrips supply. This ultimately can result in a stock out if safety levels are not substantial enough. In this case, the model needs to check if a stock out is occurring, so a solution is not given which may result in a stock out of components. The graph in Figure 28 represents this case.

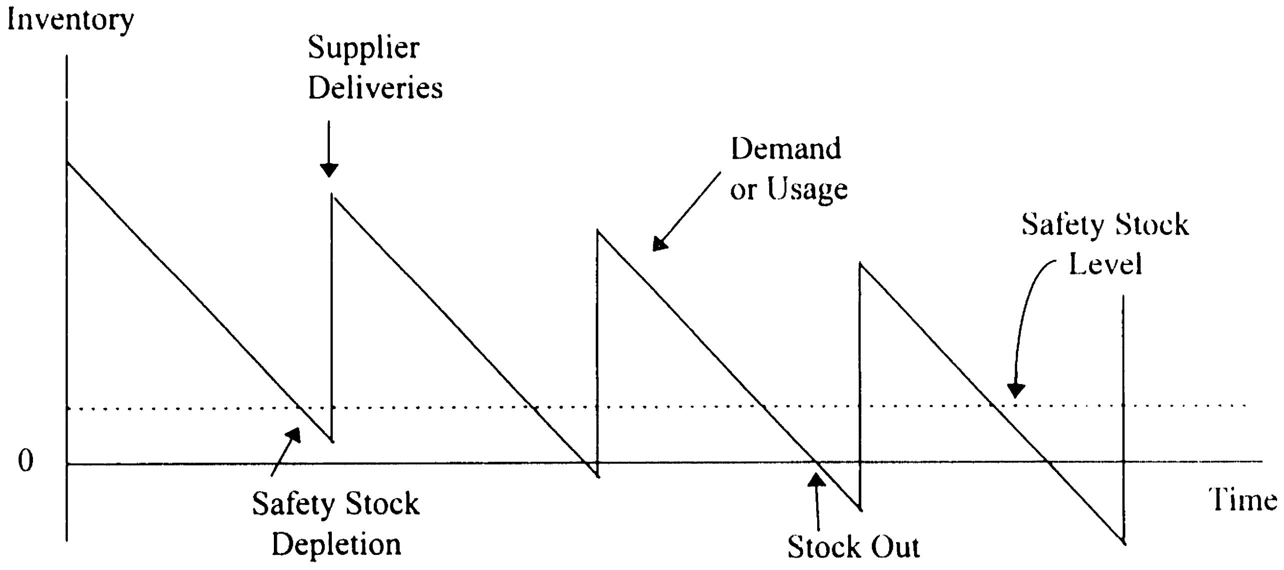

Figure 28: Demand Rate Exceeds Supplier Delivery Rate

7.4.2.3 Unevenly Spaced Supplier Deliveries

Unevenly spaced supplier shipments are the most difficult to model. Fortunately, many suppliers do not prefer shipping components in this manner. Most of these irregular shipping schedules seemed to be the result of expediting and de-expediting components as demand fluctuated. Similarly, if a supplier had quality or delivery problems, an irregular delivery schedule resulted. Since these are not intentional delivery schedules in most all cases, it was determined that providing complex modeling to attempt to optimize these types of deliveries would not provide much use. Not only might it incentivize buyers to create complex buying strategies, but much research indicates level loading factories optimizes production better. For this reason, unevenly spaced supplier delivery strategies are not modeled.

7.4.2.4 Purchasing Model Equation Derivation

When determining the overall costs associated with buying a component, the most difficult factor by far was determining the carrying charges. Although the delivery schedule varied, a mathematical representation was required that modeled all of the cases previously discussed. Including the fixed costs such as employee time, burden rates, setup costs, and delivery costs are all relatively easy, so the discussion begins with the development of an expression to accurately represent average inventory.

Beginning with one delivery per order, it is necessary to determine the size of an order and the annual demand. With these known, it is possible to calculate an average inventory over a period of time. Using the following variable notation:

Ql = The lot size (units)
D = Annual demand (units/year)
r = Demand depletion rate (units/week)
d = # weeks between deliveries (weeks)

Given a lot size Ql and annual demand D, the demand depletion rate r and delivery frequency d can be determined.

Equation 1: $r = D/52$

Equation 2: $d = Ql/r$

Figure 29 illustrates this graphically.

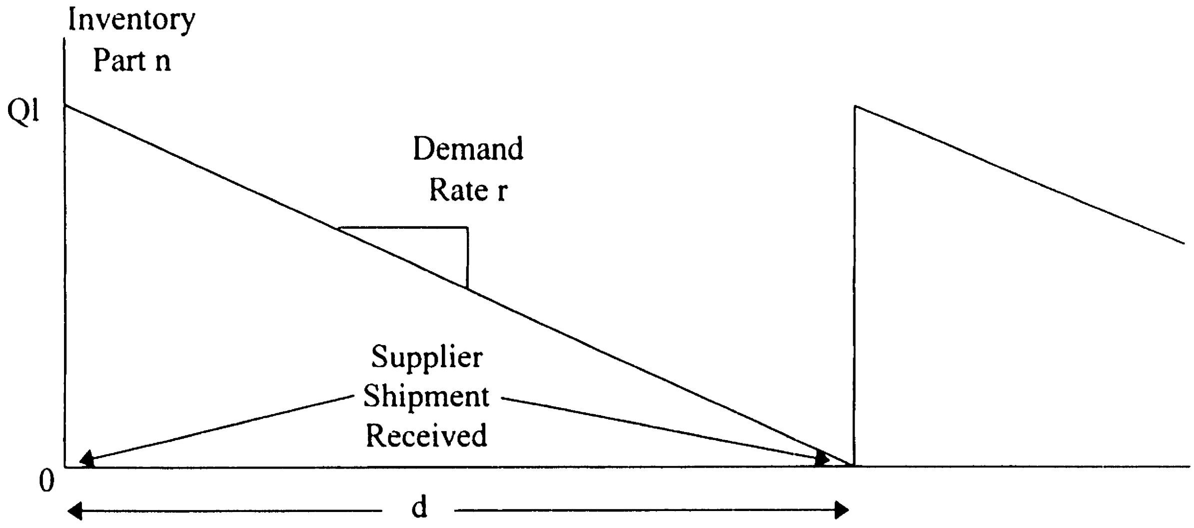

Figure 29: Graphical Representation of Demand Rate, Delivery Frequency, & Lot Size

The average inventory in the above figure is simply half of Ql over period d. While the most straightforward way to obtain this average inventory is to multiply the height of the triangle with one half, this does not allow flexibility when supply delivery rates do not equal demand rates, and inventory does not settle to zero after time d. Therefore, the following equation allows more flexibility which will be needed later.

Equation 3: Average Inventory = $Ql - r*d/2$

Equation 3 looks at rectangle Ql by d, and subtracts out the depleted range. In units of inventory, this is $r*d/2$. Multiplying this by the duration the inventory is held d, the cost per unit c, and the annual carrying charge interest rate I yields the carrying costs, h, of holding the inventory.

c = cost per unit based on supplier quote (dollars)
I = carrying cost interest rate
h = holding/carrying cost (dollars/year)

Equation 4: $h = [Ql-r*d/2]d*I*c/52$

The expression represents holding the average inventory [Ql-rd/2] for d/52 weeks at cost of $c per component with I% interest.

In the case where incoming shipments exceed customer demand and inventory slowly builds up, the average inventory is the summation of the average inventory for each delivery with the amount of remaining inventory minus the final depletion of inventory. This is graphically illustrated in Figure 30. Notice the supplier delivers four even spaced deliveries, but a new order is not received until the inventory level is depleted.

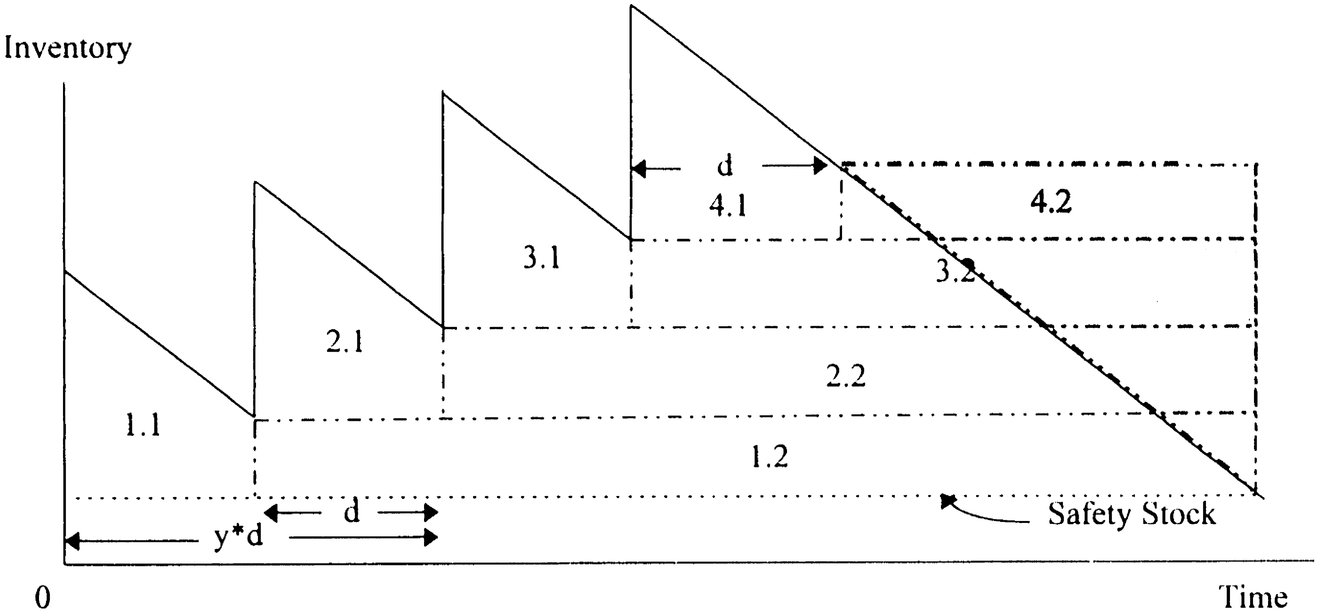

Figure 30: Generic Delivery Schedule

While Equation 3 represents the average inventory for period d, it does not allow for the inventory to increase faster than it is used. The remaining unused inventory for each period must be added on and held until depleted. This is shown above for the second delivery. Region 2.1 represents the value calculated by Equation 3. Region 2.2 is calculated below in Equation 5.

Equation 5: [Ql-r*d][Qt/r-y*d]

Where:

Qt = The total inventory committed to on the purchase order or the sum of deliveries Ql.

y = The nth delivery. In Figure 30, y = 2 because it is the unused inventory held for the 2nd delivery.

The first term, Ql-r*d, is the remaining inventory from the current order when a new shipment arrives. The term, Qt/r represents the number of weeks based on demand r that the entire order will last. y*d simply subtracts out the number of weeks already passed since the first delivery arrived. In Figure 30, this is 2*d or twice the length of two deliveries. Therefore, Ql-r*d inventory is held for Qt/r-y*d weeks. Note that as time increases, y increases, and the expression Qt/r-y*d becomes smaller. Also, notice that the inventory is carried beyond the demand curve until a new order is placed in this equation. This portion, the shaded region, is accounted for later.

Equations 3 & 5 certainly account for average inventory levels held for a given time for one shipment, but what about all of the shipments. In this case, they must be used to calculate inventory levels for each delivery. While all of the trapezoidal regions, such as Regions 1.1 and 2.1, are identical and are represented by Equation 3, rectangular regions 1.2 & 2.2 are not identical. Although Equation 5 properly calculates the value for these regions, the value of y is variable. It changes for each delivery. Equation 6 below is the series representation of the average inventory*time for all deliveries received from a supplier. Note it still does include the subtraction of the shaded region yet.

Equation 6: $$\sum_{y=1}^{n} \{[Ql-r*d/2]*d + [Ql-r*d]*[Qt/r-y*d]\}$$

Calculating this series for purchase orders with many deliveries can be tedious. Similarly, identifying optimal points among thousands of series can take a tremendous amount of time, even on a 586 CPU based computer.[20] For this reason, the series is simplified to remove the summation without affecting the desired value.

Since deliveries are constant in size and shipped to Kodak under regular intervals, this pattern is simplified in the following manner. The first and last terms of the series are determined. The average values of these two terms is determined, and then is multiplied by the number of deliveries. This provides an identical result while reducing the amount of calculation needed significantly.

Using Equation 6, the first delivery occurs when $y=1$.

$$[Ql-r*d/2]*d + [Ql-r*d]*[Qt/r-d]$$

The last delivery occurs when $y=n$, where n represents the number of deliveries.

$$[Ql-r*d/2]*d + [Ql-r*d]*[Qt/r-n*d]$$

The average of the first and last terms, multiplied by the number of deliveries n is shown in Equation 7.

Equation 7: $\{2*[Ql-r*d/2]*d + [Ql-r*d]*[(Qt/r-d) + (Qt/r-n*d)]\}*n/2$

Note that this expression can be used for all three cases of supplier deliveries. In the case where incoming shipments equal usage, the term $Ql-r*d$ is always zero, leaving $Ql-r*d/2$ held for $d*n$ weeks. The second case, where incoming shipments exceed demand, was the reason for the above derivation. What about the last case, where demand out strips delivery capabilities. In this case, note that the rectangular regions of Figure 30 become negative values, where inventory is actually subtracted from the safety stock. Once the

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[20] Initial versions of the model using series expressions required over 1 minute of calculation time on a 586 based computer.

safety stock is depleted, Boolean error checking allows the model to display a stock out condition, representing a non possible solution.

Now that the most difficult part of the model is derived, the average inventory * time determined, the remaining components of cost are now added in. First, the shaded region from Figure 30 must be determined and subtracted from the overall cost equation. Equation 8 represents this region.

Equation 8: $-1/2*[Qt-r*n*d]*[Qt/r-n*d]$

This expression allows the shaded region to be removed from the final value. A type 1 delivery schedule (incoming = outgoing) yields a value of zero in the above equation, since Qt & r*n*d are equivalent.

The safety and initial stocks must be included in the carrying costs, so the proper cost per unit can be determined. Even though they have no impact on delivery sizes or schedules, they are included so the user has an accurate representation of the total cost. These stocks are carried for the duration of the purchase order, Qt/r. Equation 9 represents the average inventory*time for these stocks.

Equation 9: $(Qs+Qi)*Qt/r$

Combining Equations 7, 8, & 9 provides an accurate representation of the average inventory*time relation for the entire order and includes the value of initial and safety stock already present. Multiplying this by the cost per component, c, and the annual interest rate, I, gives the carrying cost of the inventory based on Ql delivery lot sizes and shipping schedules determined by d and n. Dividing c*I by 52 allows the absolute carrying cost to be determined, independent of time. This is shown in Equation 10

Equation 10: $(c*I/52)*\{(Qs+Qi)*Qt/r + [2*[Ql-r*d/2]*d + [Ql-r*d]*[(Qt/r-d) + (Qt/r-n*d)]]*n/2 - 1/2*[Qt-r*n*d]*[Qt/r-n*d]\}$

Using the following variables, the total cost of ordering components is determined.

to = Time to place an order (hours)
bo = Burden rate for a buyer (\$/hour)
ti = Time to inspect a shipment (hours)
bi = Burden rate for an inspector (\$/hour)
fc = Fixed costs per delivery (\$)
Kc = Fixed costs per order, such as setup costs (\$)

Equation 11 represents the total costs, less the carrying costs, of an order placed by a buyer, using the purchase order quantity, Qt, and the cost per unit, c.

Equation 11: $Qt*c + to*bo + Kc + (ti*bi + fc)*n$

Combining equations 10 & 11 gives the total costs, including carrying charges, for a purchase order. This is shown in Equation 12. This equation is used by an Excel spreadsheet to determine an optimal buying strategy by adjusting Qt, c (using supplier quotes and dependent on Qt), d, and n. Additionally, by holding n constant and varying r, a demand sensitivity graph is generated. These will be discussed in greater detail later.

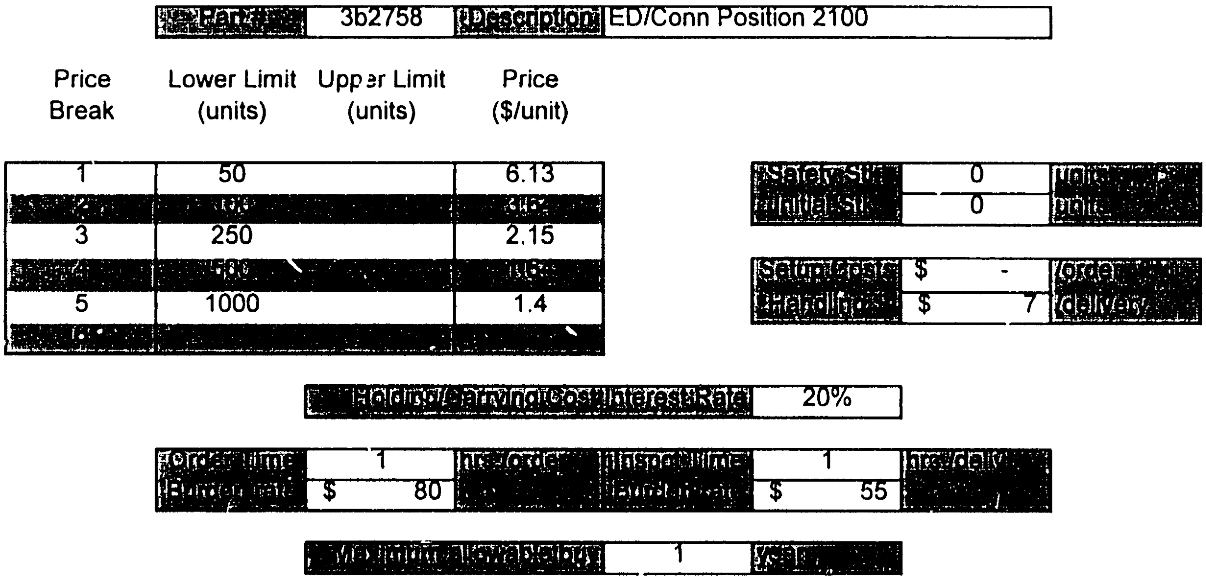
Equation 12: $Qt*c + to*bo + Kc + (ti*bi + fc)*n + (c*I/52)*\{(Qs+Qi)*Qt/r + [2*[Ql-r*d/2]*d + [Ql-r*d]*[(Qt/r-d) + (Qt/r-n*d)]]*n/2 - 1/2*[Qt-r*n*d]*[Qt/r-n*d]\}$

7.4.3 Output Parameters

The following sections describe the interface the user experiences, and uses the previously developed equation to determine the optimal buying strategy. There are three screens the user encounters. The first is the data entry screen, which allows for basic information to be entered into the model. The remaining two screens are interactive screens, which allow the user to change certain parameters. Simultaneously, an output in graphical form is generated.

7.4.3.1 *Data Entry Sheet*

The data entry sheet is shown in Figure 31, with numerical examples displayed in the input locations. It allows the user to enter the various parameters present. These parameters are fixed values and do not change under differing buying strategies. Therefore, once they are entered, they do not need to be altered, thus the user can focus attention on the output screens.



Part # 3b2758 Description ED/Conn Position 2100

Price Break	Lower Limit (units)	Upper Limit (units)	Price ($/unit)
1	50		6.13
2	100		[illegible]
3	250		2.15
4	500		[illegible]
5	1000		1.4
6			

Safety Stk 0 units
Initial Stk 0 units

Setup Costs $ - /order
Handling $ 7 /delivery

Holding/Carrying Cost Interest Rate 20%

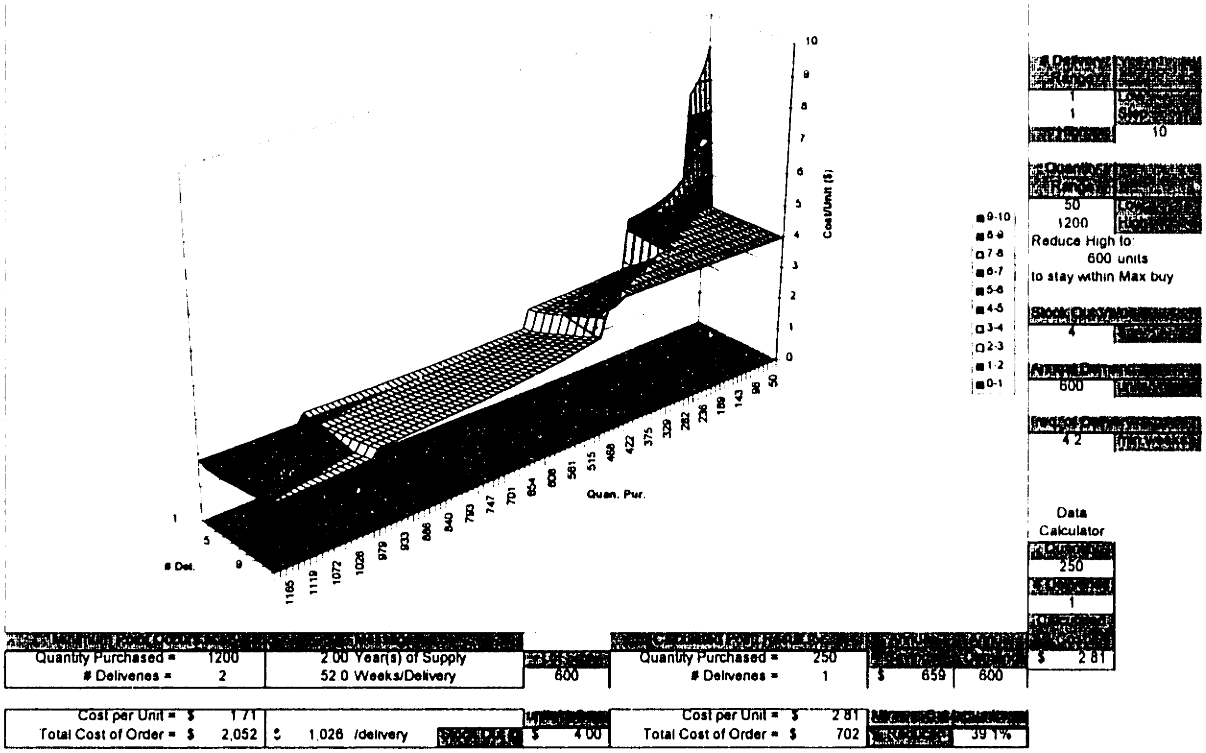
Order time 1 hrs/order
Burden rate $ 80
Inspect time 1 hrs/delivery
Burden rate $ 55

Maximum allowable buy 1 years

Figure 31: Purchasing Model Data Input Screen

7.4.3.2 *Optimal Buy Graph*

Figure 32 is one of the graphical outputs of the model. A graph is plotted of the number of deliveries and order quantity versus unit cost. The items on right side of the graph allows the user to vary graphical parameters. The first parameters the user can control is the range of the number of deliveries. The "Low" value allows the user to enter the lowest number of deliveries for display on the graph. The "Step" value allows the user to enter the increment. In this case the increment is 1, so the graph generates ten data points starting with 1, increasing 1 (step) at a time until 10 is reached. Placing a 2 in this field creates the following delivery range on the graph: 1, 3, 5, ..., 19.



1
1
10

50
1200
Reduce High to:
600 units
to stay within Max buy

4

600

4 2

250

1

$ 2 81

Quantity Purchased = 1200
Deliveries = 2

2.00 Year(s) of Supply
52.0 Weeks/Delivery

600

Quantity Purchased = 250
Deliveries = 1

$ 659 | 600

Cost per Unit = $ 1 71
Total Cost of Order = $ 2,052

$ 1,026 /delivery

$ 4 00

Cost per Unit = $ 2 81
Total Cost of Order = $ 702

39 1%

Figure 32: Optimal Buy Graph

The Quantity Range field simply uses the low and high values as the range for the purchase order quantity. The error message below stating that the High value should be reduced to 600 units is a function of the maximum allowable buy inputted on the first screen and the Annual Demand field value. In this case, with a maximum allowable buy of one year, the annual demand of 600 is outputted. While the user does not have to reduce this value for the program to generate results, the user does need to change the value if the optimal buying point is desired within the maximum buy duration limitation.

The "Stock Out" value is used to help display the area in which a stock out of components occurs. This happens when the incoming delivery schedule is not sufficient to meet demand. In order for the buyer to see this area clearly, a value is entered, in this case $4, which is highly visible on the graph, but does not limit the resolution of the remaining information. For example, if the user entered $1000, the remaining points on the graph would be dwarfed by comparison, making it impossible to see trends. Since component prices range from a few cents to hundreds or thousands of dollars, the model was developed to allow the user to choose the best setting for the "Stock Out" value. Similarly, the "Stock Out" value should not be set as the lowest point on the graph. When this happens, an error message occurs in the bottom informing the user to increase the value. Since the model uses the lowest point on the graph to determine an optimal buy point, erroneous results occur when the "Stock Out" value is set too low.

The "Annual Demand" field allows the user to enter the expected annual demand. The "freq. of delivery" field is used to enter the minimum number of weeks a supplier will regularly deliver components. In this case, the supplier will only deliver every 4.2 weeks (1 month) or longer. If component deliveries were desired on a weekly basis, this supplier would not be capable of meeting such a schedule.

The "Data Calculator" fields allow the user to input a given quantity and number of deliveries. The resultant cost is then outputted. The region below the graph provides information about the minimum point, delivery schedule, and cost. The righthand side of the message box provides a comparison between the optimal point and the "Data Calculator" point. This is used to compare the costs (and risks) of an optimal buying strategy with one the user enters.

"Annual Savings" allow the buyer to compare, on an annual basis regardless of order size, the cost differences between optimal buy and user entered points. A box showing the cost reduction, in percent, allows the buyer to see the relative savings.

7.4.3.3 Demand Sensitivity Graph

Figure 33 is the second graphical output from the model. Plotting Demand and Purchase Order Quantity versus Unit Cost allows the user to see trends in demand sensitivity. Since demand is usually not known, this graph provides a tool for analyzing changes in cost as demand varies. This can be used to assess the risk of buying different order quantities.

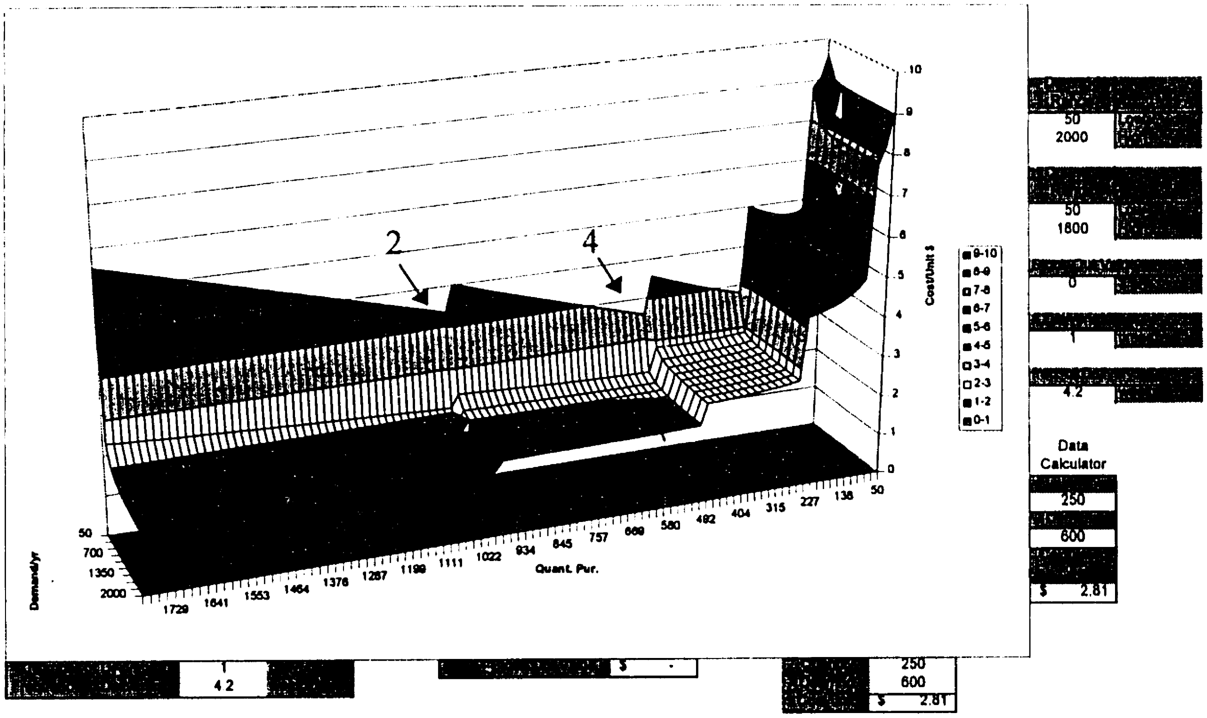


Figure 33: Demand Sensitivity Graph

For example, note Region 1 of the graph. This region represents the lowest cost option when demand is high. Note what happens if demand is not realized. The demand and quantity intersect at Region 2, and the cost increases substantially. Region 4 represents what this cost would have been, if the initial purchase occurred at Region 3. The tradeoff is between risk and cost. Taking a higher risk and buying in a larger volume allow for lower unit costs.

The data fields for the demand sensitivity graph are similar to the data fields for the optimal buy graph. Notice that the number of deliveries and their delivery frequency are held constant for this graph. Since the graph contains a three-dimensional surface plot, adding a fourth dimension for deliveries is too difficult to read for a user. Therefore, the Demand Sensitivity and Optimal Buy graphs must be used in unison to obtain the best buying strategy given uncertain demand.

7.5 Data

The model was used to help determine the expected cost savings when components were purchased using the model. In order to accomplish this, past buying data was used and entered into the model. The optimal buy data point was then compared with current buying strategies to determine expected savings.

In order to ensure the best results, the sample of components was chosen to include a wide variety of pricing, buyers, and functionality. Past quotes from suppliers were used as input to the model. The exact Kodak buying strategy was obtained by correlating the quote and part number with the delivery schedule in the MRP-II system. This provided a detailed record of the price, delivery schedule, lot size, and order duration for a component. Since Kodak does not keep a file for historical quotes, the data were limited to recent quotes sent by suppliers.

Components were randomly chosen from the six purchasing agents and buyers in optical storage. By choosing components from all of the buyers, a good cross section of electrical, mechanical, optical, specialized, and commodity type parts was generated, in part, due to the niche of components each buyer was responsible for. The components were chosen to include a wide variety of price ranges as well. Although the components were selected to provide a variety of types, most components on this list were either for the optical head or the new 2100 disk drive. More components would have been added to the list if quotes had been available. Unfortunately, more quotes were not available, which limited the component list to the twenty-nine components listed in Table 3.

The columns in Table 3 provide a description of each part with delivery and cost data. The first three columns list the internal Kodak part number, its make/buy status[21], and the component's physical description[22]. Columns four through six show the manner in which the components are currently purchased with the order size (blanket P.O.), number of deliveries for each order, and the cost for each part noted in the AIMS MRP system. The next column provides the cost for each component based on the current buying strategy when entered into the purchasing model. This cost is usually different because additional costs such as the cost of capital, buyer's and inspector's times with burden rates, and some fixed charges are included. These costs are not included in the AIMS listing, but are real. The last column lists the annual demand for each component. This is the demand entered into the purchasing model for identifying the cost per unit.

Part #	M/B	Description	Order Size	Num. Deliv.	AIMS cost/unit	Pur. Mod. cost/unit	Demand units/yr.
1	B	Part #1	50	1	$ 764.00	$ 779.57	300
2	B	Part #2	100	6	$ 400.00	$ 410.49	250
3	B	Part #3	350	15	$ 249.00	$ 254.47	225
4	B	Part #4	600	6	$ 135.00	$ 143.80	600
5	B	Part #5	525	24	$ 97.75	$ 110.23	250
6	B	Part #6	600	6	$ 102.00	$ 108.83	600
7	B	Part #7	525	24	$ 94.50	$ 95.78	250
8	B	Part #8	100	2	$ 60.63	$ 55.53	300
9	B	Part #9			$ 37.96	$ 41.95	262
10	B	Part #10	30	1	$ 39.36	$ 35.00	50
11	B	Part #11	30	1	$ 30.30	$ 35.00	50
12	B	Part #12	100	1	$ 17.37	$ 19.48	250
13	B	Part #13	50	1	$ 13.26	$ 16.32	300
14	M	Part #14	100	1	$ 13.26	$ 14.30	850
15	B	Part #15	250	1	$ 10.75	$ 11.77	600
16	B	Part #16	250	3	$ 9.09	$ 9.53	250
17	B	Part #17	50	1	$ 4.37	$ 7.30	150
18	B	Part #18	500	1	$ 4.49	$ 5.15	600
19	B	Part #19	250	1	$ 2.15	$ 2.81	600
20	B	Part #20	3000	5	$ 2.34	$ 2.54	2000
21	M	Part #21	500	1	$ 1.55	$ 2.11	225
22	M	Part #22	600	1	$ 1.55	$ 1.86	600
23	B	Part #23	1000	2	$ 1.39	$ 1.76	600
24	B	Part #24	1000	1	$ 1.21	$ 1.42	1000
25	B	Part #25	500	1	$ 0.65	$ 1.00	500
26	B	Part #26	1200	1	$ 0.75	$ 0.93	1500
27	B	Part #27	1000	2	$ 0.65	$ 0.89	1000
28	B	Part #28	500	1	$ 3.96	$ 0.86	600
29	B	Part #29	1000	1	$ 0.21	$ 0.37	1125

Table 3: Listing of Components Surveyed

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[21] Kodak uses an internal system of identifying parts manufactured internally as "make" (M) from parts made by external suppliers as "buy" (B).

[22] Part numbers and descriptions are disguised for confidentiality.

Three scenarios were run to determine the expected savings from the purchasing model. A low risk, medium risk, and high risk scenario were run. The low risk scenario allowed the model to suggest no more than a commitment to one year's worth of components from a supplier. The medium risk scenario allowed the model to suggest no more than two year's worth of components. The high risk scenario allowed the model to suggest up to a four year commitment to a supplier. While the names of these different scenarios may be misleading, they provide a quick idea of cost savings expected under different time commitments to suppliers. While the suggestion of committing to four years worth of components sounds ridiculous (which it is), the scenario can be used to compare the savings expected from such a buying strategy with those of shorter duration. Both one and two year component commitments to suppliers are not as far fetched as one may think. Since many low-volume environments contain products with long life cycles, it is entirely possible that a one or two year commitment is not a high risk. In fact, upon review of current buying strategies, many components are already purchased with one or two year commitments such as lasers and detectors. Table 3 illustrates this by comparing the order quantities with annual demand for a component. However, optimal delivery schedules are not necessarily present.

Table 4 illustrates the cost savings for each component based on the low risk buying scenario. Columns four and five provide the per unit cost savings and overall savings the component realizes annually. The sixth column lists the quantity Kodak commits to the supplier for each order placed. The last two columns provide the savings per unit and the percent the cost of the component was reduced. In a few cases, the savings is negative because Kodak's current buying strategy is greater than one year for the component. Since the low risk scenario was restricted to one year, the optimal buying strategy in this case may contain a higher cost than a component purchased by Kodak. In a few cases, the model was permitted to exceed one year's worth of purchases. This was limited to occurrences where suppliers required minimum order sizes which were greater than one year's worth of demand.

	Pur. Mod	Demand	Low Risk (about 1 year)			Low Risk	
Description	cost/unit	units/yr.	cost/unit	$/yr saved	Quan. Pur.	Sav/unit	% cost red.
Part #1	$ 779.57	300	$ 735.09	$ 13,346.00	100	$ 44.48	6%
Part #2	$ 410.49	250	$ 358.42	$ 13,016.00	250	$ 52.07	13%
Part #3	$ 254.47	225	$ 254.56	$ (21.00)	250	$ (0.09)	0%
Part #4	$ 143.80	600	$ 143.80	$ -	600	$ -	0%
Part #5	$ 110.23	250	$ 126.37	$ (4,034.00)	250	$ (16.14)	-15%
Part #6	$ 108.83	600	$ 108.83	$ -	600	$ -	0%
Part #7	$ 95.78	250	$ 99.05	$ (817.00)	240	$ (3.27)	-3%
Part #8	$ 55.53	300	$ 43.75	$ 3,532.00	300	$ 11.78	21%
Part #9	$ 41.95	262	$ 43.47	$ (342.00)	250	$ (1.52)	-4%
Part #10	$ 35.00	50	$ 34.24	$ 38.00	50	$ 0.76	2%
Part #11	$ 35.00	50	$ 34.24	$ 38.00	50	$ 0.76	2%
Part #12	$ 19.48	250	$ 17.59	$ 474.00	150	$ 1.89	10%
Part #13	$ 16.32	300	$ 14.22	$ 630.00	178	$ 2.10	13%
Part #14	$ 14.30	850	$ 10.97	$ 2,832.00	500	$ 3.33	23%
Part #15	$ 11.77	600	$ 11.32	$ 265.00	500	$ 0.45	4%
Part #16	$ 9.53	250	$ 9.09	$ 108.00	250	$ 0.44	5%
Part #17	$ 7.36	150	$ 5.28	$ 311.00	150	$ 2.08	28%
Part #18	$ 5.15	600	$ 5.15	$ -	500	$ -	0%
Part #19	$ 2.81	600	$ 2.04	$ 460.00	600	$ 0.77	27%
Part #20	$ 2.54	2000	$ 2.54	$ 6.00	3000	$ -	0%
Part #21	$ 2.11	225	$ 3.40	$ (291.00)	250	$ (1.29)	-61%
Part #22	$ 1.86	600	$ 1.86	$ -	600	$ -	0%
Part #23	$ 1.76	600	$ 2.02	$ (153.00)	600	$ (0.26)	-15%
Part #24	$ 1.42	1000	$ 1.42	$ -	1000	$ -	0%
Part #25	$ 1.00	500	$ 1.00	$ -	500	$ -	0%
Part #26	$ 0.93	1500	$ 0.92	$ 12.00	1500	$ 0.01	1%
Part #27	$ 0.89	1000	$ 0.86	$ 30.00	1000	$ 0.03	3%
Part #28	$ 0.86	600	$ 0.82	$ 23.00	600	$ 0.04	5%
Part #29	$ 0.37	1125	$ 0.36	$ 15.00	1125	$ 0.01	3%

Table 4: Low Risk Purchasing Strategy

Tables 5 and 6 illustrate the medium and high risk buying strategies used with the model. In the case of the high risk application, many supplier quotes did not include volume quotes with a high enough volume for four years. It is expected that if such quotes were available, the savings would be greater than shown in Table 6.

	Pur. Mod.	Demand	Medium Risk (about 2 years)			Medium Risk	
Description	cost/unit	units/yr	cost/unit	$/yr. saved	Quantity Pur.	Sav/unit	% cost red
Part #1	$ 779.57	300	$ 735.09	$ 13,346.00	100	$ 44.48	6%
Part #2	$ 410.49	250	$ 322.84	$ 21,911.00	500	$ 87.65	21%
Part #3	$ 254.47	225	$ 237.22	$ 3,881.00	500	$ 17.25	7%
Part #4	$ 143.80	600	$ 133.73	$ 6,042.00	1200	$ 10.07	7%
Part #5	$ 110.23	250	$ 107.72	$ 627.00	500	$ 2.51	2%
Part #6	$ 108.83	600	$ 107.06	$ 1,062.00	1200	$ 1.77	2%
Part #7	$ 95.78	250	$ 93.73	$ 513.00	600	$ 2.05	2%
Part #8	$ 55.53	300	$ 38.55	$ 5,094.00	600	$ 16.98	31%
Part #9	$ 41.95	262	$ 41.95	$ -	500	$ -	0%
Part #10	$ 35.00	50	$ 28.70	$ 315.00	100	$ 6.30	18%
Part #11	$ 35.00	50	$ 28.70	$ 315.00	100	$ 6.30	18%
Part #12	$ 19.48	250	$ 17.59	$ 474.00	150	$ 1.89	10%
Part #13	$ 16.32	300	$ 14.22	$ 630.00	178	$ 2.10	13%
Part #14	$ 14.30	850	$ 10.97	$ 2,832.00	500	$ 3.33	23%
Part #15	$ 11.77	600	$ 10.20	$ 941.00	1000	$ 1.57	13%
Part #16	$ 9.53	250	$ 8.92	$ 153.00	500	$ 0.61	6%
Part #17	$ 7.36	150	$ 5.16	$ 329.00	234	$ 2.20	30%
Part #18	$ 5.15	600	$ 4.34	$ 488.00	1010	$ 0.81	16%
Part #19	$ 2.81	600	$ 1.71	$ 659.00	1200	$ 1.10	39%
Part #20	$ 2.54	2000	$ 2.53	$ 18.00	4000	$ 0.01	0%
Part #21	$ 2.11	225	$ 2.11	$ -	500	$ -	0%
Part #22	$ 1.86	600	$ 1.31	$ 334.00	1000	$ 0.55	30%
Part #23	$ 1.76	600	$ 1.70	$ 39.00	1200	$ 0.06	3%
Part #24	$ 1.42	1000	$ 1.42	$ 1.00	1106	$ -	0%
Part #25	$ 1.00	500	$ 0.89	$ 57.00	1000	$ 0.11	11%
Part #26	$ 0.93	1500	$ 0.92	$ 15.00	1690	$ 0.01	1%
Part #27	$ 0.89	1000	$ 0.52	$ 367.00	2000	$ 0.37	42%
Part #28	$ 0.86	600	$ 0.66	$ 120.00	1200	$ 0.20	23%
Part #29	$ 0.37	1125	$ 0.32	$ 63.00	2250	$ 0.05	14%

Table 5: Medium Risk Purchasing Strategy

	Pur. Mod.	Demand	High Risk (Best possible)			High Risk	
Description	cost/unit	units/yr.	cost/unit	$/yr. saved	Quantity Pur.	Sav/unit	% cost red.
Part #1	$ 779.57	300	$ 735.09	$ 13,346.00	100	$ 44.48	6%
Part #2	$ 410.49	250	$ 288.20	$ 30,572.00	1000	$ 122.29	30%
Part #3	$ 254.47	225	$ 220.96	$ 7,539.00	1000	$ 33.51	13%
Part #4	$ 143.80	600	$ 133.73	$ 6,042.00	1200	$ 10.07	7%
Part #5	$ 110.23	250	$ 102.74	$ 1,873.00	1000	$ 7.49	7%
Part #6	$ 108.83	600	$ 107.06	$ 1,062.00	1200	$ 1.77	2%
Part #7	$ 95.78	250	$ 93.67	$ 527.00	990	$ 2.11	2%
Part #8	$ 55.53	300	$ 34.33	$ 6,329.00	1200	$ 21.20	38%
Part #9	$ 41.95	262	$ 39.30	$ 595.00	1000	$ 2.65	6%
Part #10	$ 35.00	50	$ 28.70	$ 315.00	100	$ 6.30	18%
Part #11	$ 35.00	50	$ 28.70	$ 315.00	100	$ 6.30	18%
Part #12	$ 19.48	250	$ 17.59	$ 474.00	150	$ 1.89	10%
Part #13	$ 16.32	300	$ 14.22	$ 630.00	178	$ 2.10	13%
Part #14	$ 14.30	850	$ 10.97	$ 2,832.00	500	$ 3.33	23%
Part #15	$ 11.77	600	$ 10.20	$ 941.00	1000	$ 1.57	13%
Part #16	$ 9.53	250	$ 8.82	$ 177.00	1000	$ 0.71	7%
Part #17	$ 7.36	150	$ 5.16	$ 329.00	234	$ 2.20	30%
Part #18	$ 5.15	600	$ 4.04	$ 666.00	1514	$ 1.11	22%
Part #19	$ 2.81	600	$ 1.67	$ 680.00	2400	$ 1.14	41%
Part #20	$ 2.54	2000	$ 2.52	$ 40.00	8000	$ 0.02	1%
Part #21	$ 2.11	225	$ 1.48	$ 121.00	1000	$ 0.63	30%
Part #22	$ 1.86	600	$ 1.31	$ 334.00	1000	$ 0.55	30%
Part #23	$ 1.76	600	$ 1.66	$ 60.00	2400	$ 0.10	6%
Part #24	$ 1.42	1000	$ 1.42	$ 1.00	1106	$ -	0%
Part #25	$ 1.00	500	$ 0.89	$ 57.00	1070	$ 0.11	11%
Part #26	$ 0.93	1500	$ 0.92	$ 15.00	1690	$ 0.01	1%
Part #27	$ 0.89	1000	$ 0.31	$ 572.00	4000	$ 0.58	65%
Part #28	$ 0.86	600	$ 0.63	$ 136.00	2000	$ 0.23	27%
Part #29	$ 0.37	1125	$ 0.15	$ 246.00	4322	$ 0.22	59%

Table 6: High Risk Purchasing Strategy

To determine the annual savings expected from the purchasing model's use, the following assumptions were made.

1. Existing and historical quotes on the 29 components were used.
2. Delivery schedules and component cost were retrieved from the AIMS system for determining historical or planned purchasing practices for the 29 components.
3. The actual annual demand (historical) was used for the mature components.
4. For the new components, the Annual Operating Plan (AOP) was multiplied by .625 to obtain expected annual demand for the new component[23]. This is a conservative estimate.
5. A carrying cost or cost of capital for inventory was assumed to be 20% for all 29 components.
6. The assumption was made that all orders required about one hour of a buyer's time with an hourly burden rate of $80 per hour. The time estimation is considered to be conservative.
7. The assumption was made that all incoming deliveries require about one hour to process/inspect at a burden rate of $55 per hour. This time includes receiving the shipment on the dock, moving it to the vault, unpacking the components, entering the arrival in the MRP system, and inspecting any components. This time estimate is considered to be conservative.
8. The model was used to calculate actual costs for CURRENT buying strategies of the 29 components based on the data from the AIMS system and compared with the three scenario's optimal purchasing outputs.

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[23] Past actual annual component demands were very close to their historical AOP demands times .625. The author believes this yields a more accurate and conservative result. If the demands are closer to the AOP, the savings will be even greater.

Since no historical data had been taken on the uncertainty of demand per component, it was not factored into the expected cost savings. If such data had been available, it would have been used to help determine the confidence of these expected savings. To compensate for this, conservative estimates were used. It is hoped that any deviation from the results will tend toward even greater cost savings.

Table 7 shows the cost savings expected based on the above assumptions. The current purchasing costs were calculated by entering the twenty-nine components into the purchasing model (using the ***current*** Kodak buying policy), calculating the unit cost of each component based on this buying policy, and multiplying its unit cost by the annual demand. The annual purchase cost for all 29 components is shown in Table 7[24].

Each component's optimal buying strategy was also determined for each of the three scenarios, by adjusting the *maximum allowable buy* accordingly. Each scenario was run using the purchasing model to determine the optimal buying strategy for each of the twenty-nine components. The annual purchasing costs for all twenty-nine components were calculated the same way the annual costs for the *current* buying strategy were determined. These values were then compared with Kodak's current costs. The percent cost reduction based on the three scenarios is shown in Table 7.

Table 8[25] lists the total costs for components and Materials Management personnel for 1995, and the projected costs for 1996 in the top row. The increase in these costs for 1996 is the result of an expected increase in production volume. The sample data (29 components) was then used to determine *total cost* savings for the Optical Storage Products business unit by multiplying the percent cost reduction for each scenario, from Table 7, by the *total costs* listed in the first row of Table 8. These costs totaled $2

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[24] This data has been significantly disguised to protect confidential information. Actual and relative costs have been altered. The percent cost reduction expected is real however.
[25] ibid.

million in 1995 and were expected to increase to $2.3 million for 1996[26]. For example, $205,620 ($2.3 M x 8.94 %) savings are expected for 1996 using the medium risk scenario.

Model Run	**Annual Cost**	**Annual Savings**	**% Cost Reduction**
Current Policy	$1,000,000	$0	0 %
Low Risk	$956,600	$43,400	4.34 %
Medium Risk	$910,600	$89,400	8.94 %
High Risk	$886,500	$113,500	11.35 %

Table 7: Projected Annual Savings for Low, Medium, & High Risk for the 29 Components

Scenario	1995 - Expected Savings ($2,000,000 total costs)	1996 - Projected Savings ($2,300,000 total costs)
Current Policy	$0	$0
Low Risk - 4.34 %	$86,800	$99,800
Medium Risk - 8.94 %	$178,800	$205,620
High Risk - 11.35 %	$227,000	$261,050

Table 8: 1995 & 1996 Annual Savings Using the Purchasing Model for Optical Storage

7.6 Discussion of Results

An attempt was made to keep all assumptions on the conservative side. Because Kodak does not use an Activity Based Cost tracking system, it was difficult to determine the actual costs incurred when procuring components. By placing all existing buying

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[26] Materials Management costs are included in these values, though, the data is still disguised.

practices in the model, and comparing the new calculated costs with each of the three scenarios, a more accurate representation of cost savings was possible.

Many low cost components had high unit costs due to frequent ordering under current buying practices. Since the buyer's time was worth considerably more than the component, it was harder to spread the cost of the buyer over the components, resulting in higher unit costs. In these cases, buyers are unaware of the expense their time places on the unit cost of components. It is arguable that assuming one hour of ordering time is excessive for less expensive components. When contacting the supplier, receiving quotations, evaluating different suppliers, monitoring current inventory levels in the AIMS system, and tracking the status of such components is considered, this is not unreasonable.

Higher priced components were perceived to have high inventory carrying costs by buyers. The model suggests that there are substantial savings when committing to higher volumes from suppliers and carrying the inventory. In almost every case, buyers undervalued the benefits from volume discounting and overvalued the cost of carrying inventory (see Tables 3-6). The ordering and inspection/receiving times are conservative for these high priced, highly specialized components. In most, if not all cases, these costs are an insignificant percentage of the entire cost for purchasing high cost components.

Increasing the order and inspection times for components only increases order commitments and delivery lot sizes in the model. Since the optimal buying strategies are already a significant stretch from current buying practices, it was assumed that these values were adequate.

The use of this model highlights systemic changes which are needed to fully benefit from its use. Since longer order commitments increase risk, it is essential that cross functional teams and/or people are used to help determine the best buying strategy. This requires the following functional groups to participate. All functions must consider whether the optimal buying strategy commitment (time) will conflict with possible changes in components or discontinuation of the product.

1. Product development & manufacturing engineers: Are needed to help determine if changes will be made to the component before all parts are used to completion.
2. Marketing: Is needed to provide product life and expected annual demand information to the team.
3. Purchasing: Is needed to help determine the input parameters to the model. They are expected to have information on commodity components at Kodak, noting which components can be purchased through commodity management. They also interact with the suppliers regularly, and are used as the interface between Kodak and its suppliers.
4. Assembly line operators: Are needed to provide assembly problems with specific components. Components that are difficult to assemble should not be purchased in higher volumes because it is expected engineering improvements will be made (given proven cost benefit analysis).
5. Quality: Is needed to provide quality data to the team. The most important function quality can play is by determining if suppliers quality is increased, or decreased, due to the new order sizing. Perhaps ordering larger lots improves learning at the supplier. On the other hand, quality problems may be hidden for long periods of time.
6. Finance: Is needed to determine current cash flow capabilities. Many optimal buying strategies require increased cash flow due to larger commitments. Finance is also expected to provide updated cost of capital data.

The old saying that, "You can't get something for nothing" applies here. Cost reductions gained by using the purchasing model require more communication between functional groups within Kodak. No one group has enough information to make an educated purchasing decision for a given component. It is clear that higher cost components should be a priority for the team, since the greatest cost reductions can occur from such components. In conclusion, the model forces a cross functional approach to component procurement. Without this approach, it is not possible to realize the potential costs savings from the model.

8. Conclusion

Both cycle time and cost can be reduced significantly in a low-volume environment. While the methodology to achieve these reductions is straightforward, it is necessary to determine the pertinent parameters to achieve these goals. Three major issues were addressed and analyzed in this thesis. First, the use of a Kanban system can be applied to a low-volume manufacturing unit successfully. Second, cycle time can be significantly reduced in a low-volume manufacturing environment using this Kanban system. Third, significant component cost reductions can be achieved by optimizing buying strategies of such components.

8.1 Kanban Systems Work in Low-Volume Manufacturing Environments

The research conducted at Kodak suggests that a Kanban manufacturing system can successfully be used in a low-volume manufacturing environment. Kanban signaling is virtually identical to practices used in higher volume environments[27]. The signaling practice of, "building toward the hole," provided an easy solution to the problems generated by the two-tray-no-card Kanban signaling suggested by Costanza. While this is not a significant variation, it did reduce the number of signaling errors in low-volume production.

Kanban sizing for low-volume environments is easier when the equation represents process parameters in weekly demand and days of production. This allows quick calculation of Kanban sizing while lessening confusion. Since many process steps in

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[27] This is based on the successful implementation of signaling described in The Quantum Leap by John Costanza. Additional comparisons with the literature of Toyota no genba-kanri: kanban hoshiki no tadashii susumekata (Kanban and just-in-time at Toyota: management begins at the workplace). Japan Management Association, Tokyo. 1985; support this hypothesis as well.

low-volume environments require more than one day to process, classical Kanban sizing equations can confuse users. This confusion is generated by process steps requiring long, unmanned, segments. Calculating replenishment times in hours for such process steps is a classical approach, which is not ideal for certain low-volume manufacturers.

Cross training within low-volume manufacturing environments was considerably more difficult, due to the increased complexity of individual process steps. This presents challenges to low-volume factories implementing Kanban systems, since employee cross training is difficult. Without a cross trained work force, the effectiveness of the Kanban system can be reduced, especially as demand shifts from one process step to the next. It seems that learning two or three process steps well is preferable to learning four or more partially.

Production scheduling of multiple products through the factory using the same production equipment improved with the use of the Kanban system. Operators used Kanban signaling cues to determine needed production. This seemed to allow the factory to meet present demand needs while reducing overall work-in-process.

Finally, the Kanban system seemed to begin a continuous improvement feedback loop, allowing problems to be tackled. As the Kanban system exposed problems in the production process, engineering tackled the problems. Once problems were solved, this reduced variability in the production system allowing the Kanban sizing to be reduced, since the excess work-in-process was unneeded. This in turn exposed lesser problems, continuing the process. Due to the limited duration of the internship, only one iteration of this loop was witnessed.

8.2 Cycle Time can be Significantly Reduced

Cycle time was significantly reduced under Kanban production. Within a four month period, the KOH CD sub-assembly process witnessed a 75% reduction in cycle time.

KOH 2000 sub-assemblies had still not seen a critical mass of volume, though early results suggested similar improvements could be expected as well.

Measuring total production cycle time was very effective for tracking cycle time in the factory. Unfortunately, measuring the cycle time of individual process steps did not provide accurate information on these steps. The nature of low-volume production makes it difficult to separate actual production time from idle time. Since an operator does not necessarily concentrate on one unit of production through the entire process step without taking breaks, or performing other needed production work, it is not possible to accurately obtain detailed process cycle times in low-volume environments.

8.3 Component Costs can be Significantly Reduced

Using an optimal buying strategy determined by the purchasing model developed in this thesis allows low-volume manufacturers to minimize component cost. This is done by assessing optimal purchase order size, delivery lot sizes, and delivery schedules. These parameters, when compared with risk, can be used to successfully determine a buying strategy on a *per component basis* allowing reductions in component cost.

There was some discussion about using a Kanban system between suppliers and the business unit to facilitate component transactions, once optimal purchasing parameters were chosen. This works well for components with multiple deliveries; however, many components are shipped once a year or less. In these cases, the use of a Kanban system between such suppliers does not seem to create a significant advantage.

By using the purchasing model developed in this thesis, a low-volume manufacturing unit currently using an ABC purchasing policy for determining component buying strategies can expect a reduction in overall costs. At Kodak, these component cost reductions ranged from 4.34% to 8.94% without engaging in high risk buying practices. Similar results are expected in other manufacturing organizations with similar volumes, cost structures, and current purchasing policies.

Additionally, the use of a cross functional team is necessary when using the purchasing model to optimize buying practices. Without this cross functional skill, it is not possible to assess the risk associated with committing to order sizes, lot sizes, and delivery schedules with suppliers. By using purchasing, engineering, marketing, finance, and assembly line operators together, users of the model can predict the time for expected component obsolescence, discontinuation, or likelihood of engineering changes. This provides a good estimation of component needs for a fairly long duration. Without such cross functionality, relevant information needed to assess risk is not used, and hence, sub-optimal decisions can occur.

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Appendix A - KOH Process Steps

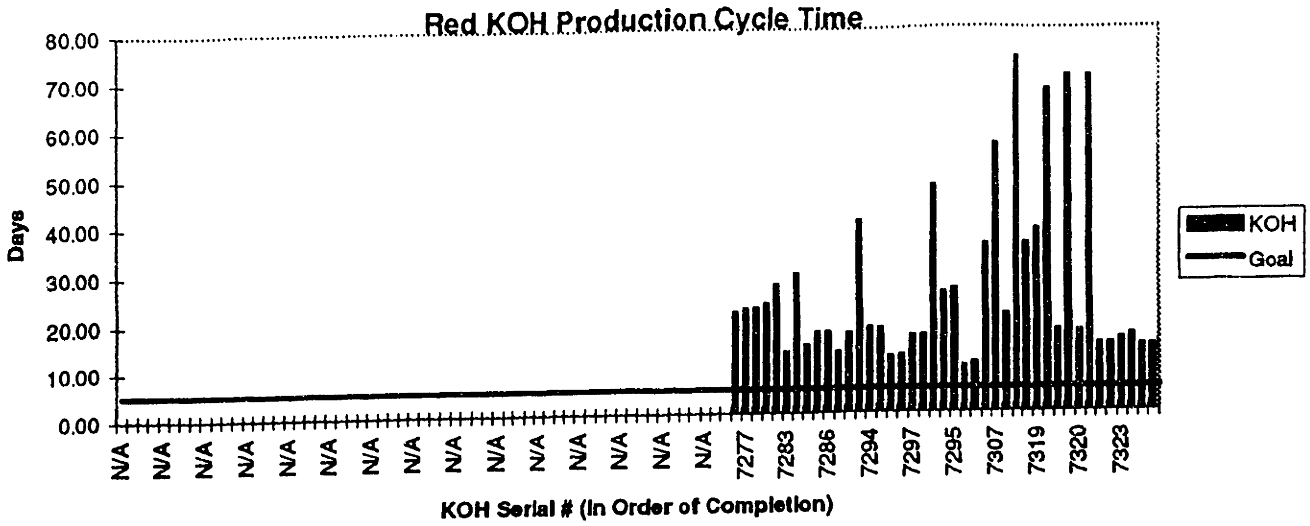
# Employees	5	1st shift	man*hrs/day	30						
# Employees	0	2nd shift	man*hrs/day	0						
# Employees	0	3rd shift	man*hrs/day	0						
Kanban Stage			Sub Assembly Station - Stage S							
Total hrs/shift	8.5									
Work hrs/shift/per.	6									
Total # shifts	1									
Sub Stage			Laser Subassembly					Optical Subassembly		
Product			2000/2100	All	CD/2100	CD	All	2000/2100	2000/CD/2100	2000
Part #			3b2538/?	no #	992677/?	992677	992521	3b2539	3b2543/992513	3b2533
Process	Parts		Laser	Manual LI	T-Filt./Pork	Laser	Front	Cover	Quarter	Cyl. Lens
Step	Release		Mount	for Laser	Chop/HFI	Module Ay	Facet Det	Glass Cap	Wave Plt.	Front Facet
Labor Min.			2.5	10	40	15	2.5	2.5	2.5	0.01
Unattend. Min			0.01	0.01	720	0.01	720	720	720	0.01
Rework %			0	5	0	20	0	0	0	0
Labor Capac.			1	1	1	1	1	1	1	1
Unattend. Cap			1	1	50	1	50	100	100	1
Utilization factor			1	1	1	1	1	1	1	1
# Cycles for Unatt.			51000	51000	1	51000	1	1	1	51000
Thruput unit/hr			24.00	5.71	1.50	3.33	8.33	16.67	16.67	6000.00
Thruput u/day			144.00	34.29	9.00	20.00	50.00	100.00	100.00	36000.00
Cycle Time (hrs)			0.04	0.18	12.67	0.30	12.04	12.04	12.04	0.00
KOH 2000			1	1	0	0	1	1	1	1
KOH 2100			1	1	1	0	1	1	1	0
KOH CD			0	1	1	1	1	0	1	0
Cum. Cycle t (hrs)										
KOH 2000			0.04	0.22	0.22	0.22	12.26	24.30	36.34	36.34
KOH 2100			0.04	0.22	12.88	12.88	24.93	36.97	49.01	49.01
KOH CD			0.00	0.18	12.84	13.14	25.18	25.18	37.23	37.23
			Constraint	labor needed	for each	step listed above				
	# needed	hrs need.	sumprdct by head							
KOH 2000	6	53.1185	0.041666667	0.175	0	0	0.041666667	0.041666667	0.041666667	0.000166667
KOH 2100	10	54.404167	0.041666667	0.175	0.666666667	0	0.041666667	0.041666667	0.041666667	0
KOH CD	8	47.383333	0	0.175	0.666666667	0.3	0.041666667	0	0.041666667	0
Total	24	154.906								
Weekly hours	150									
Available										
Hours needed										
1 KOH 2000	8.8530833									
1 KOH 2100	5.4404167									
1 KOH CD	5.9229167									

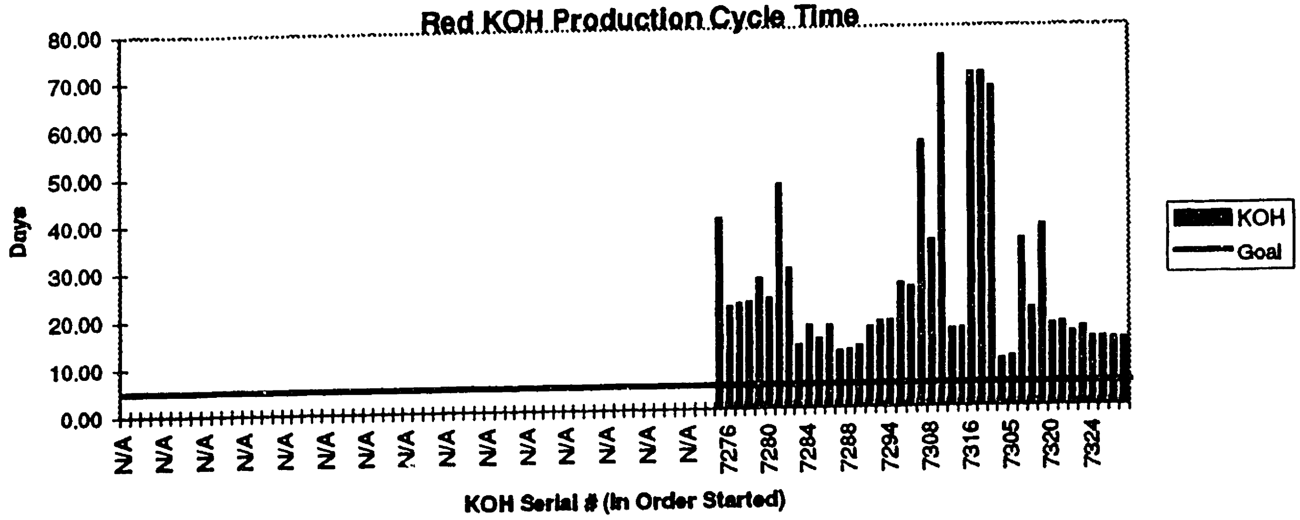
				All KOH - Stage 1		All KOH - Stage 2				KOH 200
CD - Flex	Actuator Modification									
CD	2000/CD	2100	All	All	All	All	CD	2000/2100	2000/2100	
992952	3b2641/3b2640	3b2641	same	3b2541/992507		unchanged				2
Head	Actuator	BODE	Actuator	Optical	Pointing	Laser	Actuator	Actuator	Cap	Detector
Flex	Painting	Measure.	Modification	Stk. Mnt.		Collimation	Installation	Installation	Installation	Allignment
25	5	10	60	15	12.5	35	20	20	8	45
0.01	0.01	0.01	0.01	720	0.01	0.01	0.01	20	30	0.01
0	0	0	0	25	25	30	10	50	10	5
1	1	1	1	1	1	1	1	1	2	1
1	1	1	1	10	1	1	1	1	2	1
1	1	1	1	1	1	1	1	1	1	1
51000	51000	51000	51000	1	51000	51000	51000	26	17	51000
2.40	12.00	6.00	1.00	1.33	3.84	1.32	2.73	2.00	5.15	1.27
14.40	72.00	36.00	6.00	8.00	23.04	7.91	16.36	12.00	30.91	7.62
0.42	0.08	0.17	1.00	15.31	0.26	0.76	0.37	1.00	0.70	0.79
0	1	0	1	1	1	1	0	1	1	1
0	0	1	1	1	1	1	0	1	1	0
1	1	0	1	1	1	1	1	0	0	0
36.34	36.43	36.43	37.43	15.31	15.57	16.33	16.33	17.33	18.03	18.82
49.01	49.01	49.18	50.18	15.31	15.57	16.33	16.33	17.33	18.03	18.03
37.64	37.73	37.73	38.73	15.31	15.57	16.33	16.70	16.70	16.70	16.70
0	0.083333333	0	1	0.3125	0.260416667	0.758333333	0	0.5	0.146666667	0.7875
0	0	0.166666667	1	0.3125	0.260416667	0.758333333	0	0.5	0.146666667	0
0.416666667	0.083333333	0	1	0.3125	0.260416667	0.758333333	0.366666667	0	0	0

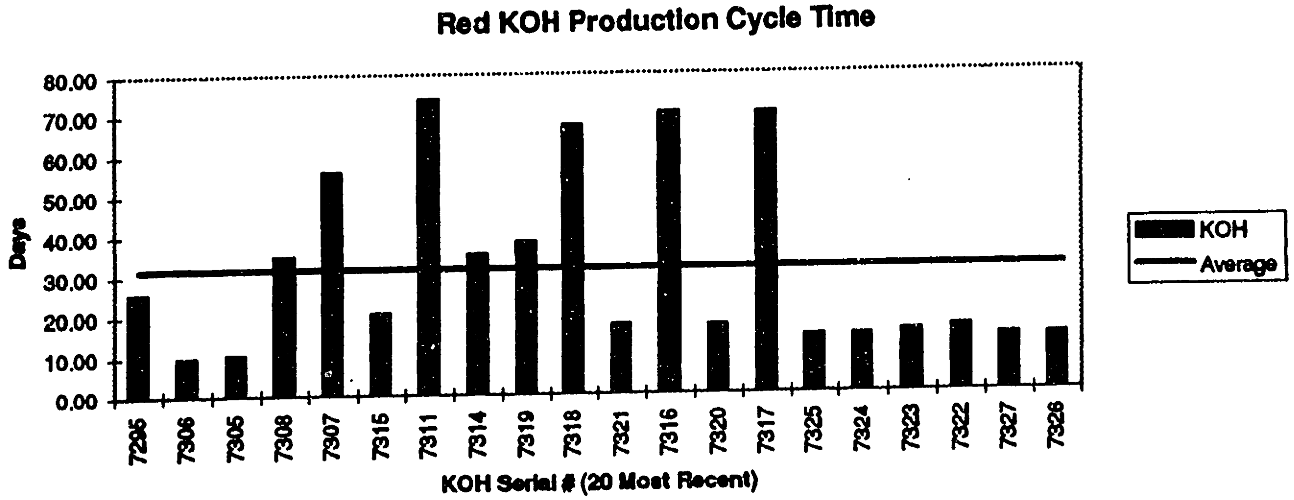
- Stage 3	KOH 2100/CD - Stage 3		Stage 3.ADL		Stage 3.CD	KOH 2000 Testing - Stage 4				
							Test Tool			Run-In
00	CD/2100		2000/2100	All	CD	2000	2000	2000	2000	2000
3b2544	992507	992506	same		992506		3b2600			3b2600
Pre-Amp	Head Flex	Detector	BODE	Grey	Spin Stand	Set	LI Drive	Test	6.8	14.8
Installation	Installation	Allignment	Plot	Glue		Potentiomtr	& Servo	Tool	Read	Autocycle
40	20	40	5	10	15	5	30	135	10	10
0.01	0.01	0.01	0.01	720	80	0.01	0.01	0.01	70	30
0	0	5	5	0	20	0	0	10	0	0
1	1	1	1	1	1	1	2	2	4	4
1	1	1	1	100	1	1	1	1	4	4
1	1	1	1	1	1	1	1	1	1	1
51000	51000	51000	51000	1	7	51000	51000	51000	8	17
1.50	3.00	1.43	11.43	6.00	0.97	12.00	4.00	0.81	5.33	11.33
9.00	18.00	8.57	68.57	36.00	5.83	72.00	24.00	4.85	32.00	68.00
0.67	0.33	0.70	0.09	12.17	1.90	0.08	0.50	2.48	1.33	0.67
1	0	0	1	1	0	1	1	1	1	1
0	1	1	1	1	0	0	0	0	0	0
0	1	1	0	1	1	0	0	0	0	0
19.48	19.48	19.48	19.57	31.74	31.74	31.82	32.32	34.80	36.13	36.80
18.03	18.36	19.06	19.15	31.32	31.32	31.32	31.32	31.32	31.32	31.32
16.70	17.03	17.73	17.73	29.90	31.80	31.80	31.80	31.80	31.80	31.80
0.666666667	0	0	0.0875	0.166666667	0	0.083333333	0.5	2.475	0.166666667	0.166666667
0	0.333333333	0.7	0.0875	0.166666667	0	0	0	0	0	0
0	0.333333333	0.7	0	0.166666667	0.3	0	0	0	0	0

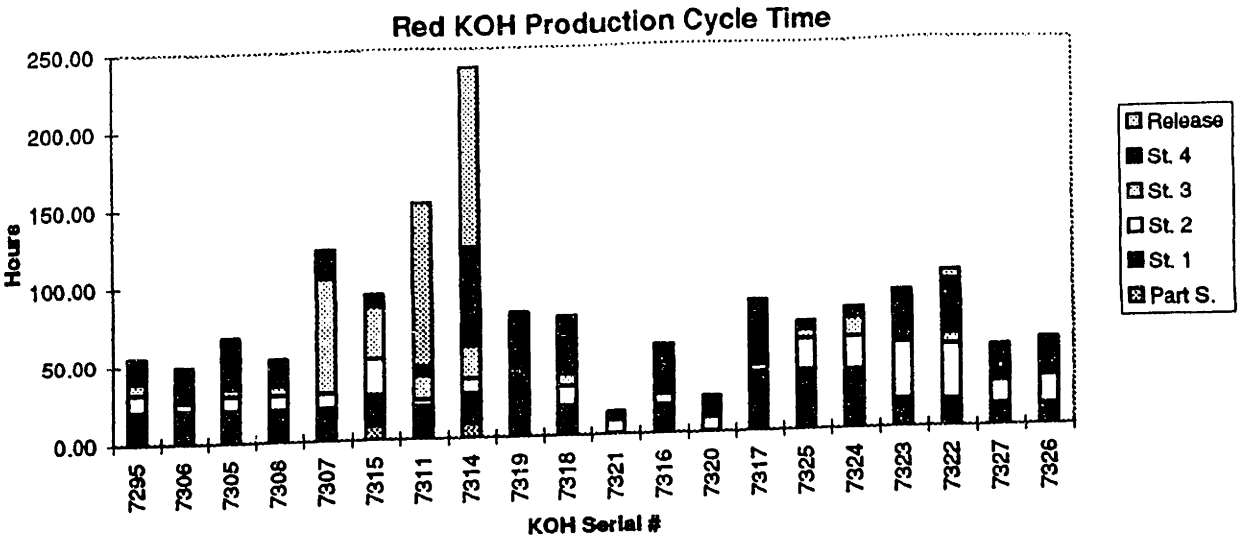
2000
CES
Testing
20
2400
5
4
4
1
0.5
0.32
1.90
42.35
1
0
0
79.15
31.32
31.80
0.35
0
0

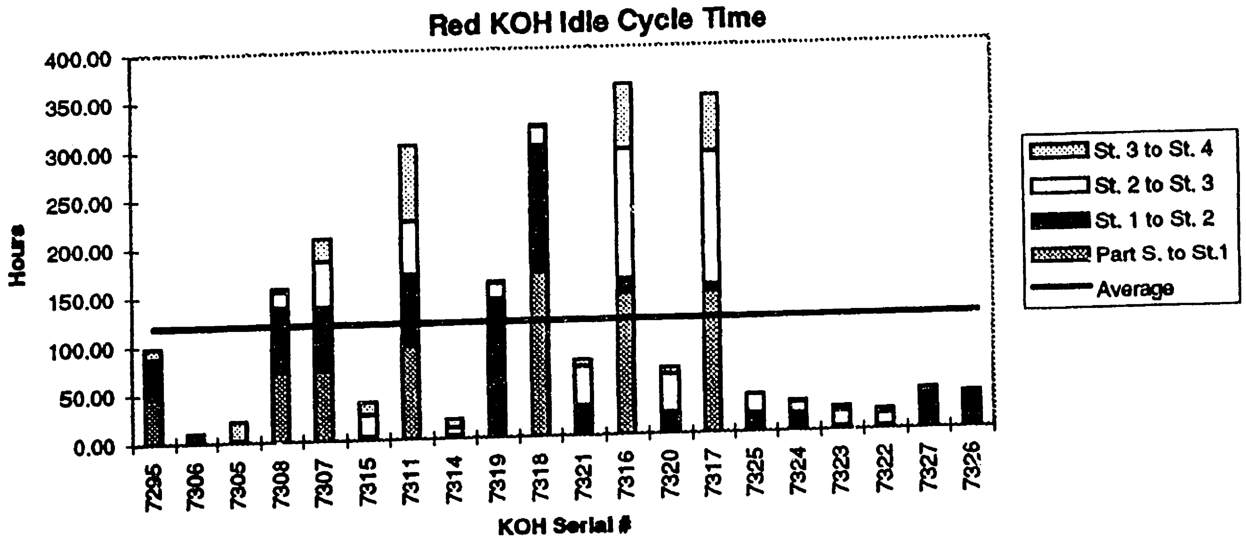
Appendix B - KOH 2000 Cycle Time

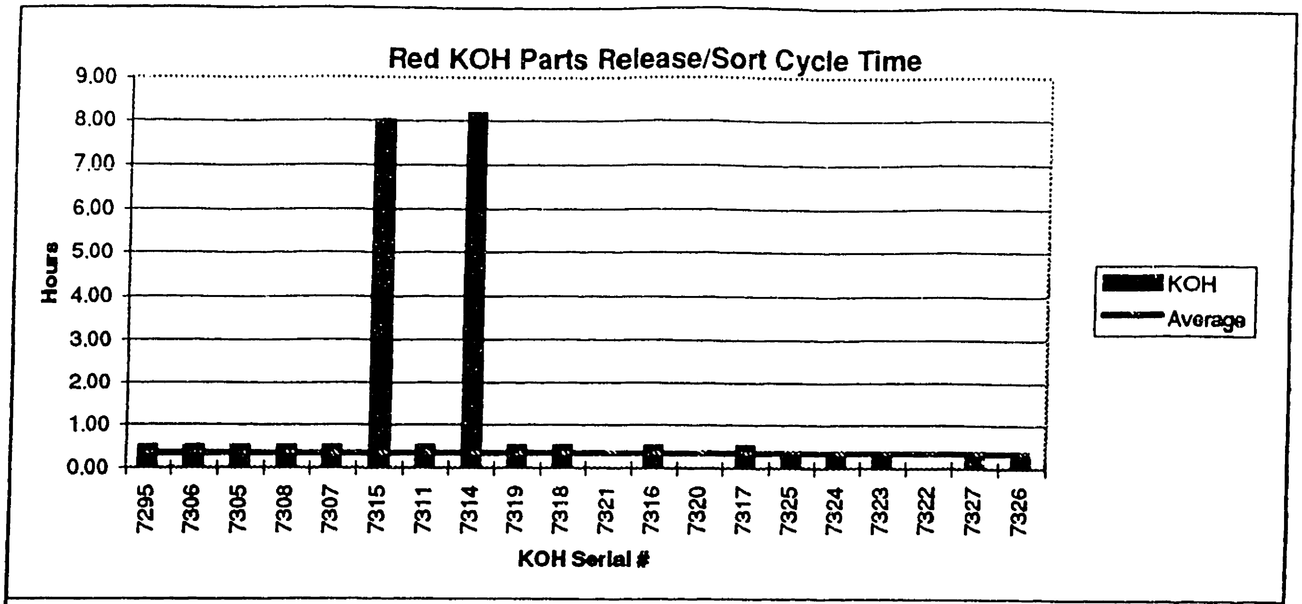

Red KOH Production Cycle Time

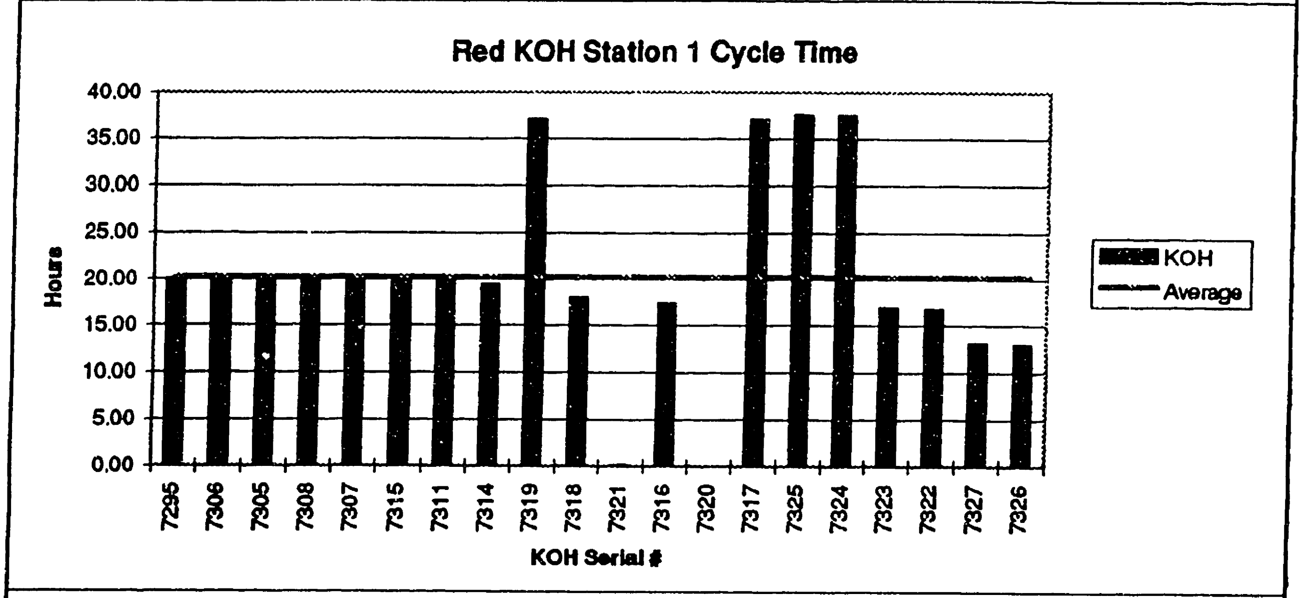

Red KOH Production Cycle Time

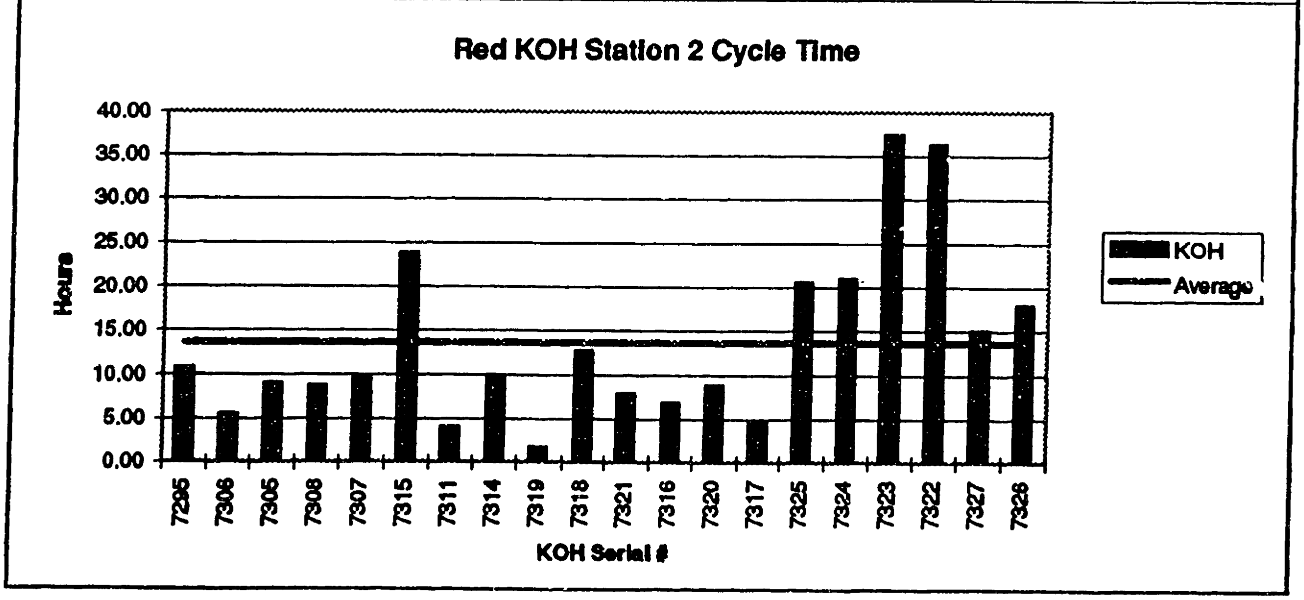

Red KOH Production Cycle Time


Red KOH Production Cycle Time

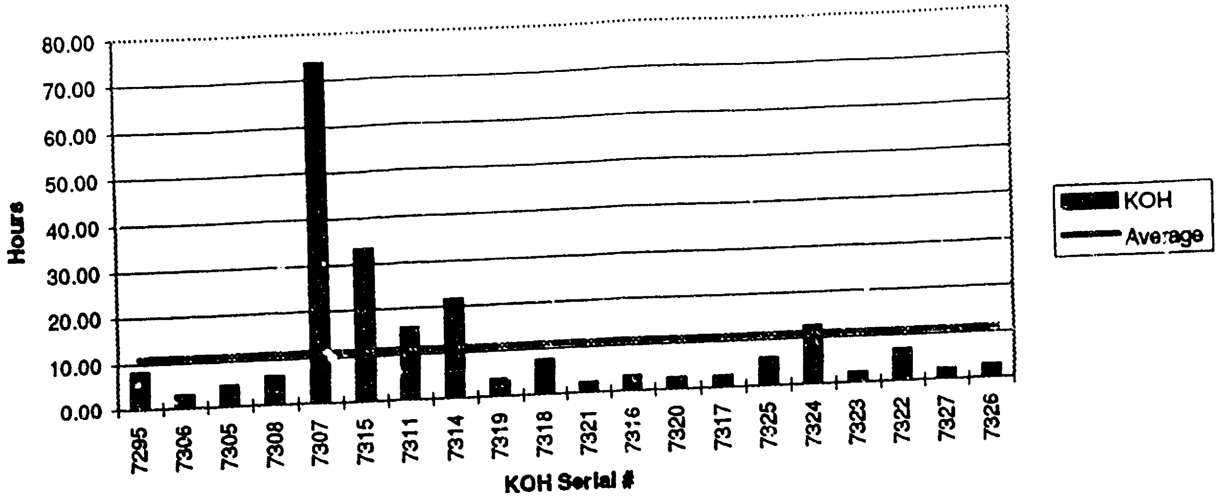

Red KOH Idle Cycle Time


Red KOH Parts Release/Sort Cycle Time
Hours
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
7295
7306
7305
7308
7307
7315
7311
7314
7319
7318
7321
7316
7320
7317
7325
7324
7323
7322
7327
7326
KOH Serial #
KOH
Average

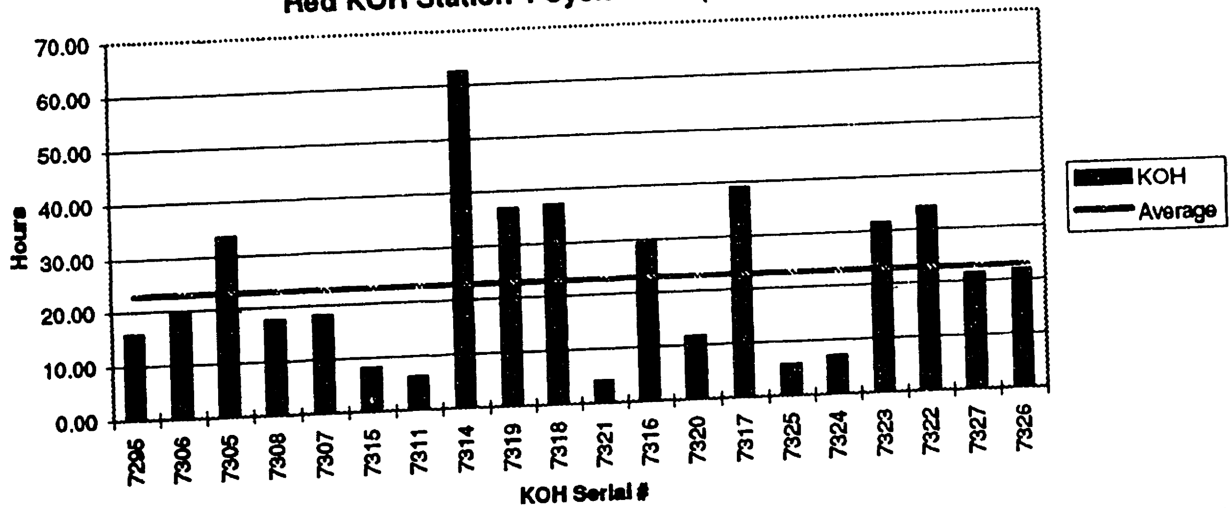

Red KOH Station 1 Cycle Time
Hours
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
7295
7306
7305
7308
7307
7315
7311
7314
7319
7318
7321
7316
7320
7317
7325
7324
7323
7322
7327
7326
KOH Serial #
KOH
Average


Red KOH Station 2 Cycle Time
Hours
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
7295
7306
7305
7308
7307
7315
7311
7314
7319
7318
7321
7316
7320
7317
7325
7324
7323
7322
7327
7326
KOH Serial #
KOH
Average

Red KOH Station 3 Cycle Time



Red KOH Station 4 Cycle Time (Testing/Re-Work)



Red KOH Final Release Cycle Time