

Implications and Implementation of Manufacturing Cycle Time Reduction

by

Scott Jacobson

B.S. Electrical Engineering, University of Illinois, College of Engineering, 1990

Submitted to the Sloan School of Management and the
Department of Electrical Engineering and Computer Science
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Signature of Author _____
Sloan School of Management
Department of Electrical Engineering and Computer Science

Certified by _____
Stanley Gershwin, Senior Research Scientist, Thesis Advisor
Department of Mechanical Engineering

Certified by _____
Donald Rosenfield, Senior Lecturer, Thesis Advisor
Sloan School of Management

Accepted by _____
Lawrence S. Aheln, Director of Master's Program
Sloan School of Management

Accepted by _____
Arthur C. Smith, Chairman, Committee on Graduate Students
Department of Electrical Engineering and Computer Science

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OF TECHNOLOGY

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Abstract

Manufacturing cycle time, the time required to build an order, is a key contributor to the overall success of a factory. Customer satisfaction (cost, quality and service), shareholder satisfaction and employee satisfaction can improve with improvements in manufacturing cycle time. While the relationship is not necessarily causal, cycle time can be considered a proxy or leading indicator of the factory health.

Eastman Kodak Company management has set several aggressive "10X" goals for all manufacturing operations. These goals require that the operations look beyond traditional continuous improvement and instead turn to more revolutionary changes. The thesis project focus is on a 10X reduction in manufacturing cycle time. The relationship between manufacturing cycle time and customer satisfaction is examined. Manufacturing cycle time is not addressed in isolation. Instead, cost, quality and service are related to cycle time and are used to balance the goals of improvement. Both continuous improvement and factory redesign are used as methods to improve overall customer satisfaction.

The thesis project was carried out in a circuit board assembly factory at Eastman Kodak. Data analysis, combined with observation, led to a discovery of the highest leverage items effecting manufacturing cycle time: work-in-process inventory levels and a large number of queues, the method of order release, variability, and large lot sizes. Continuous improvement efforts focused on many of these areas. As the goals and weaknesses of the factory became more clear, a redesign was necessary to remove inhibitors to reaching the goal of one day manufacturing cycle time. A team developed a new factory design incorporating changes in the layout, organization and systems. As implementation of the new design is completed, continuous improvement can begin again.

The continuous improvement efforts resulted in a reduction of the manufacturing cycle time from 8.7 days to 4.9 days with an associated reduction in work-in-process inventory of \$750,000. The factory redesign team, formed in September, 1996, began implementation of the new design in December of 1996. Implementation has reduced factory floor space from 20,000 to 12,000 square feet, valued at approximately \$1 million.

Thesis Advisors:

Vince Andrews, Eastman Kodak Company

Professor Donald Rosenfield, MIT Sloan School of Management

Professor Stanley Gershwin, MIT Department of Mechanical Engineering

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1. Introduction

One of Kodak's circuit board assembly factories (CBA1) has set a goal of reaching a 10X reduction in manufacturing cycle time in just 3 years time. CBA1's improvements are a result of reduction of work-in-progress (WIP) inventory. As these gains reach a plateau, CBA1 is looking for new ways to continue their improvement.

CBA1 manufactures a high mix of low volume circuit board products with varying complexity. Three distinct manufacturing lines exist and products have been designed to fit on one of the three. Limited flexibility exists in the movement of products or resources from line to line. Each of the three manufacturing lines has both automated surface mount "pick-and-place" capability and differing levels of manual and through-hole component placement capability.

Manufacturing operations is managed with an MRP system for both materials and production planning. Most products are made to order, but some finished goods inventory is maintained as a buffer. Raw materials are released into production based on an MRP "release date" (a "push" method) derived from the customer due date.

Manufacturing cycle time is measured as the average of all jobs' time from actual release until the job is shipped to either the customer or finished goods inventory. All jobs are weighted equally. Monthly averages are typically reported to smooth out the variability within any given month. The cycle time in early 1996 was 8.7 days. The goals for the end of 1996 and 1997 are 5.5 days and 1 day, respectively.

Analysis was performed to understand the overall cycle time, its distribution, and the underlying contributors. Bar charts were created which reflect the workcenter's impact on the overall cycle time. Traditional analysis had only looked at the areas that had the largest independent cycle time, leading to improvement efforts in areas that often contributed very little to the overall improvement of the factory. Data was analyzed

using several methods to not only find the biggest impact items, but to understand the effects of the planning organization and manufacturing management had on cycle time.

WIP levels contribute the most to the cycle time. In the past, high WIP levels were used to motivate operators when demand was high. Overtime was worked when WIP levels became very high. Much smaller, but next on the list of contributors is batch size.

(While batch sizes themselves contribute to WIP, the WIP effects go well beyond this.)

Initially (with high WIP levels), batch size has little effect on cycle time. But as WIP levels come down, batch sizes begin to add complications into the manufacturing process. Batch sizes are a function of costs (planning, purchasing, changeover), expected customer demand and work content. As a result of this, batch sizes tended to be large to gain a perceived reduction in cost. Ignored in the calculation are such costs as inventory and inventory carrying costs, quality, and service.

1.1 Thesis Objective

The objective is to present the analysis and actions to improve the cycle time performance in CBA1 and recommendations for additional action. This document analyzes the technical and organizational issues relevant to assembling circuit boards at Eastman Kodak Company. In addition, this document discusses the merits of cycle time reduction efforts.

1.2 Thesis Overview

Chapter 2. Manufacturing Cycle Time: This chapter discusses of how cycle time is defined and why it should be the focus for improvement efforts. The relationship between cycle time and overall customer satisfaction is explained and improvement methods and costs are discussed. Finally, an overview of the literature is presented.

Chapter 3. Background: This chapter gives an overview of the technologies used in CBA1, including surface mount and through-hole assembly. The manufacturing and business processes are explained. The factory layout and organizational structure is

illustrated and discussed. The chapter is completed with a discussion of the products, product volumes and complexity.

Chapter 4. Analysis: This chapter starts with a discussion of how cycle time is measured in CBA1. Next, data on the current cycle time is presented and discussed. Then the cycle time is dissected by observing the cycle time for each manufacturing line, major operation, and workcenter. Conclusions are extracted from the analysis and discussed.

Chapter 5. Continuous Improvement: This chapter documents the continuous improvement efforts that helped reduce the manufacturing cycle time. These improvements included creation of a visual tool to aid in work prioritization and to highlight the level of work on the floor. A CONWIP was implemented to manage job releases and standard lead times were reduced, both of which aided in the reduction of WIP levels.

Chapter 6. Factory Redesign: The factory redesign process, new factory layout and organization are discussed. The details of major changes in the factory design and organization are presented. The chapter concludes with a list of post-redesign improvements necessary to continue progress toward the goal of reaching one day cycle time.

Chapter 7. Conclusions: This chapter raps up the thesis with a summary of the lessons learned, followed by a list of longer term recommendations for continued improvement in CBA1.

1.3 Results

Continuous improvement at CBA1 resulted in a reduction of cycle time by over 3.5 days for a WIP reduction of over \$750,000. The factory redesign resulted in a simplification of the manufacturing process, reducing the number of queues and the number of discreet process steps. The redesign eliminated one of the surface mount assembly lines and configured the remaining two lines to be identical so that they can function as one team.

Consolidation of similar processes and queues for each of the three lines has aided in reducing the amount of manufacturing floor space from 20,000 to 12,000 square feet. Variability in output has been reduced by implementing a balanced, around-the-clock operation.

2. Manufacturing Cycle Time

2.1 Definitions

Manufacturing cycle time is defined as the time from the initial decision to build a specific order for a product until the time it ships to the customer or to finished goods inventory. Manufacturing cycle time is a component of the response time, which is the time it takes to respond to a customer's order. If no materials and component inventories are held in the system and orders are built only upon receipt, components must first be ordered from suppliers. Once received, the manufacturer builds the desired product and ships it to the customer. The component lead time is the period from order to receipt of components. Figure 2-1 illustrates this concept.

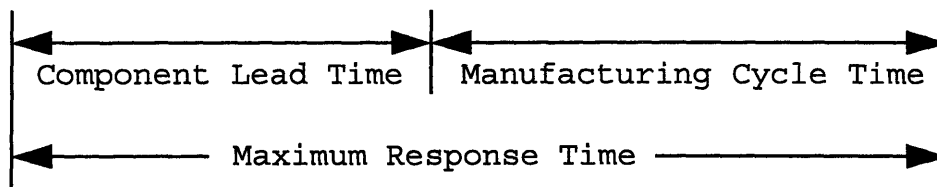


Figure 2-1: Cycle Time

If a manufacturer (or supplier) wants to improve response time, finished goods inventory can be held, allowing shipment of product upon order receipt. Alternatively, a supply of raw components can be kept on hand and the desired product can be manufactured when needed. A combination of these two methods is typically used.

In many instances, a manufacturer is both a consumer and a supplier. Raw materials are consumed to produce finished goods. These finished goods may be the raw materials for the next manufacturer in the supply chain. For example, to assemble circuit boards for a laser printer, transistors, resistors and other raw materials must be purchased. Once purchased, the board is assembled. This board is both the finished good from the board assembler and a raw material for the laser printer assembler.

If the time to produce is long, the manufacturer must keep a supply of the finished components on hand to give his customers the proper service level need. The longer the manufacturer's time to receive components and to build the product, the more inventory that must be held.

Any manufacturer's service level is a function of his inventory and manufacturing cycle time. A manufacturer is effected by his suppliers, but he too is a supplier to the next stage of the production of a final product.

Component lead times are also critical in determining the amount of raw component inventories and the finished goods inventory. If component lead times can be reduced then both of these inventories may be reduced.

2.2 Why Manufacturing Cycle Time

Manufacturing cycle time itself should not be the goal of factory improvements. Manufacturing cycle time should be viewed as the enabler to improve other important areas that contribute to the overall success of a factory: Customer Satisfaction (Cost, Quality and Service), Shareholder Satisfaction and Employee Satisfaction. While it can be difficult to measure some of these things, cycle time can be considered a proxy or leading indicator of the factory health, just as housing starts are an indicator of the US's economic health and direction.

If a manufacturer reduces the manufacturing cycle time, finished good inventory can be reduced while maintaining the same customer service level. This is advantageous because the finished goods inventories are very expensive, tying up large amounts of capital. This inventory can also be costly to manage and requires floor space to store.

In addition, reducing the inventory reduces the time lag from when a component is manufactured to when the customer uses it. If defects are generated in manufacturing and not discovered until the component is used by the customer, a potential risk exists of generating more defects of the same type. When manufacturing cycle time is reduced,

defect data is collected more closely to when the defect was created. This aids both in the reduction of the number of similar defect that are made before the problem is noticed and the speed at which the defect cause is corrected. Correcting the problem is more rapid because more information is available on the cause of the problem. If a process step is performed incorrectly and it is a week before the problem is detected, it is unlikely that an operator will recall what happened. Thus, reducing the cycle time increase that rate at which learning can occur. The desired effect is an improvement in manufacturing quality.

The return on improved quality is even faster cycle time resulting from the reduced need for special attention to defects and problems. This creates a reinforcing loop where improved quality leads to faster cycle time which lends to further quality improvement. This is often called “cycles of learning”.

Customer service is improved when manufacturing cycle time is reduced because factories can respond faster to the customers needs. If an urgent manufacturing order is taken, a factory with a long manufacturing cycle time will have to make an extra effort to produce the components in the desired time. Not only does this require added effort (possibly extra equipment setups, supervisors’ and planners’ time), it also delays the production of other orders in the factory. But if the manufacturing cycle time is low, a special request can be made with no addition effort and no impact to other orders.

By reducing cycle time, quality and service are improved. Since less defects are generated and less added effort is needed, costs are reduced. In addition, in the effort to reduce cycle time non-value added manufacturing process steps are typically eliminated. These steps were usually needed at some point in the past but often the environment has changed such that they are no longer necessary. But their purpose is often forgotten and the steps are not eliminated. In an effort to reduce cycle time, all steps of the process are re-evaluated to understand their need.

Also, some process steps exist simply because manufacturing cycle time is so long. An example of this, which will be discussed in more detail later, is the need to wash circuit boards. Solder flux (a residue that remains after soldering) must be removed from a circuit board within 24 hours of application. If a board is soldered three times within a 24 hour period, it only needs to be washed once. But if a circuit board takes five days to be soldered the three times, it must be washed after each of the three soldering steps.

Figure 2-2 summarizes the impact that cycle time has on customer satisfaction. All relationships are positive: if cost, quality or service improves, customer satisfaction should also improve. (Of course, if competition is improving faster, customer satisfaction may actually decrease.) The arrows between quality and cycle time illustrate the “Cycles of Learning” that result from rapid feedback: the sooner defects are discovered, the sooner the manufacturing process can improve.

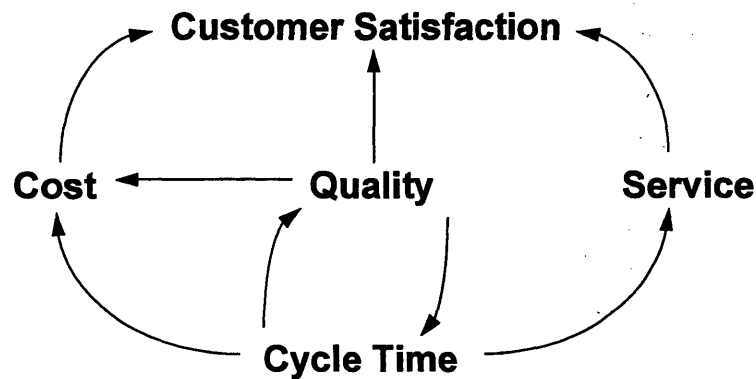


Figure 2-2: Cycle Time's Effect on Customer Satisfaction

2.3 Improvement Methods

The literature contains many methods of improvement, including Total Quality Management (TQM), Just In Time (JIT) methods, Total Productive Maintenance (TPM), Demand Flow Technology (DFT), and Theory of Constraints (TOC) approaches. A closer look at each of these methods show how the intended impact will be similar. For example, TQM puts the emphasis on improving product and manufacturing quality. As shown in Figure 2-2 improvements in quality lead to improvements in cycle time. To

further improve quality, cycle time must be reduced to provide data in a more timely manner. This cycle time improvement then filters back to improvements in cost and service. The end effects of TQM and cycle time reduction are synonymous.

Similar arguments can be made for the other improvement methods. Given that the end results are the same, the methods differ in tools and initial focus. The point to make here is that it is not so important which of the methods are used, but that one (or some) is chosen and improvements made. In CBA1, we have chosen tools and ideas from several of the methods to create our own methodology that could be termed “Cycle Time Reduction”.

2.4 Improvement Costs

While adding new capital equipment can be expensive, most improvements can be made with small incremental expenses. Although it can be difficult to quantify, return on these investments can be very quick. Traditional cost/benefit analysis leaves out things such as associated improvements in quality, service and inventory levels. Through careful analysis proper justification can be made. For example, the purchase of a new test equipment would result in a reduction in cycle time (and the associated WIP) of half of one day. The value of the WIP alone is far greater than the cost of the equipment. Similar analysis can show the value of hiring more employees or working some overtime even though “average demand” can be met.

2.5 Literature Survey

A recent Business Week article on Dell Computer Corporation described the key to its success as “In a word: speed”.¹ Upon receipt, fully custom orders are built and on a delivery truck in 36 hours. This speed has allowed Dell to keep low inventories and reduce costs, enough to underprice competitors 10% to 15%. Dell’s responsiveness has

¹ McWilliams, “Whirlwind on the Web”, *Business Week*, April 7, 1997, p. 134.

allowed them snare contracts away from competitors. This has generated a 91% increase in profits and a 47% increase in revenues in 1996, while the rest of the industry is growing at a much gentler pace.²

Womack shows many examples from the automotive industry in which “lean” manufacturing improves costs and quality. In one particular example, a General Motors plant and a Toyota plant are compared. The Toyota factory uses 50% of the time of the GM factory to assemble a car while creating one third the number of defects. Inventories at the Toyota factory are a fraction of the inventories at the GM factory.³ These differences translate directly into cost advantages for Toyota.

The improvements at both Dell and Toyota are results of the same focus: eliminating waste. Womack defines waste as “activity which absorbs resources but creates no value: mistakes which require rectification, production of items no one wants so that inventories and remaindered goods pile up, processing steps which aren’t actually needed, movement of employees and transport of goods from one place to another without any purpose, groups of people in a downstream activity standing around waiting because an upstream activity has not delivered on time, and goods and services which don’t meet the needs of the customer.”⁴ This definition provides a list of wastes that, fortunately, can be systematically sought out and eliminated.

Karmarkar suggests that lead times (which include cycle times) are indices of manufacturing improvement. Shorter lead times mean improved responsiveness and flexibility, and lead to savings by eliminating the costs for storing and moving WIP inventories and buffer stock.⁵ Karmarkar further asserts that long manufacturing cycle

² *ibid.*

³ Womack, Jones, and Roos, The Machine that Changed the World, p. 81.

⁴ Womack and Jones, Lean Thinking, p. 15.

⁵ Karmarkar, “Getting Control of Just-in-Time”, Harvard Business Review, September/October, 1989, p. 123.

times can erode a company's competitive position because of poor response to changes in demand.⁶ In the case of Dell, the corollary certainly applies.

A hybrid approach is recommended for a factory such as CBA1. A pull system, such as a CONWIP (Constant WIP), leaves control and responsibility at the factory operations level, offering incentives for lead-time management. An MRP system is used for materials planning and coordination of customer requirements.⁷ Hopp and Spearman are in favor of CONWIP, which synchronizes releases to departures, keeping the WIP level constant. It is easily observable and requires less WIP on average over a pure push system for the same throughput.⁸

⁶ Karmarkar, Kekre, and Kekre, "Lotsizing in Multi-Item Multi-Machine Job Shops", IIE Transactions, September 1985, p. 290.

⁷ Karmarkar, "Getting Control of Just-in-Time", Harvard Business Review, September/October, 1989, p. 127.

⁸ Hopp and Spearman, Factory Physics, p. 334.

3. Background

The section describes the state of manufacturing at Kodak's Circuit Board Assembly Area #1 (CBA1) as it existed in the summer of 1996. CBA1 builds products mostly for internal customers which include digital camera, laser printer, medical imaging products and scanners. CBA1 is of strategic importance because it manufactures a multitude of relatively low volume, high-end products which would be difficult to outsource at a reasonable price. These high-end products are critical to maintaining Kodak's image and presence in digital imaging.

3.1 Technology

The two basic types of circuit board assembly technologies are "through-hole" and "surface mount". The physical difference in the technologies are how electronic components are fastened to the board. Through-hole components have leads (the wires that electrically connect the component to the circuit board) that pass through holes in the board, while surface mount components' leads are connected on the surface of the board without passing through it. The two technologies are illustrated in Figure 3-1.

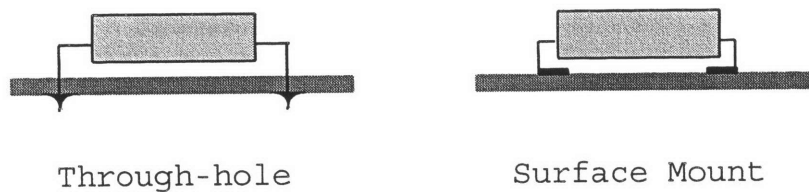


Figure 3-1: Technology Comparison

3.1.1 Through-hole

Through-hole technology components are placed onto a prefabricated circuit board either by hand or with automated equipment. The circuit boards have metal circuits embedded in the board and holes are drilled to accommodate components. These holes are ringed with metal to provide an electrical contact point. Once all components are in place, the board is passed over a solder wave. This solder wave coats all exposed metals on the

bottom of the board, creating a solder joint between a component lead and the hole in the board. Figure 3-2 illustrates this process.

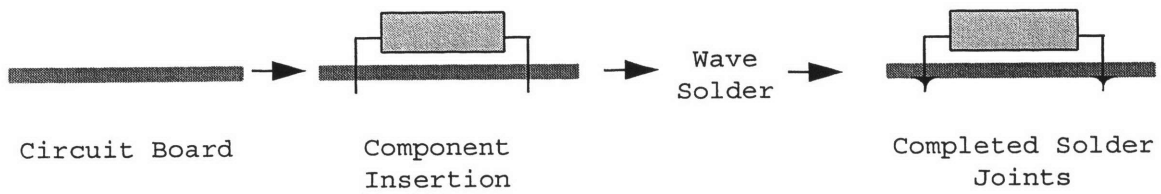


Figure 3-2: Through-hole Technology Process Flow

3.1.2 Surface Mount

Surface mount technology components are placed on the surface of the circuit board. Prior to component placement, a solder paste is placed in the desired locations. Once the paste and component are in place, the board is passed through an oven which heats the board surface to the melting point of the solder paste. Upon cooling, a solder joint is created between the component leads and the board. Figure 3-3 illustrates this process.

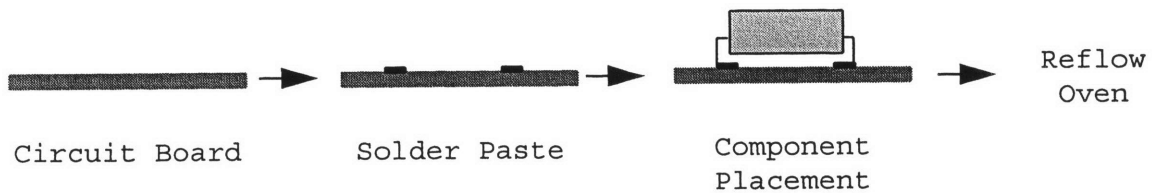


Figure 3-3: Surface Mount Technology Process Flow

Surface mount technology is a relatively new. It allows components to be placed on both sides of a circuit board, reducing the size of the board or allowing for increased complexity. In addition, components are typically smaller than the equivalent through-hole component. Component placement is performed by machine. Although these machines have higher capital costs than through-hole equipment, improved placement rates, component density and quality levels reduce the costs below that of through-hole placement.

3.1.3 Other

In addition to these types of placement technologies, components may be soldered in place by hand using a solder iron or a solder fountain. These methods are used for difficult to solder components, fragile components, or for components that can not be washed.

3.2 Manufacturing Process

The manufacturing process for a circuit board consists of six major steps shown in Figure 3-4. All boards at a minimum go through the first and last steps: kitting and shipping. The number of other steps needed depends on the design of the board. Some boards may require all of the other steps, while some may just require one.

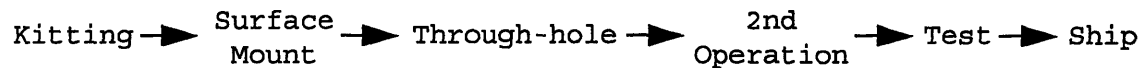


Figure 3-4: Process Flow

3.2.1 Kitting

Once a lot is released, the kitting operation pulls from inventory or local distributors all the components that are necessary to build the board. Next, feeders are set up for surface mount components and the leads are formed for through-hole components. Once the kit is complete, it is delivered to the next step in the process.

3.2.2 Surface Mount

The next step for most boards is the surface mount process. As described in Section 3.1.2, surface mount components are soldered to the board surface. The process of soldering leaves a residue of a corrosive soldering agent that must be washed off the board. This wash is performed in a large continuous flow washing machine.

Some boards will have surface mount components placed on both sides of the board. If this is the case, the board remains in the area for another pass down the surface mount

line. If the board will require wave soldering for through-hole devices, the surface mount devices on the second side are glued instead of soldered to the surface. If solder is used, the boards are washed.

A visual inspection is performed on the boards after soldering. This is typically a 100% inspection to check for proper component placement, alignment, and solder joint quality. Any defects are repaired immediately and the data is entered into a database.

3.2.3 Through-hole

The next step is the through-hole process, as described in Section 3.1.1. At CBA1, through-hole components are inserted by hand in an assembly line fashion and then boards are passed through the solder wave. If components were glued to the bottom side of the board in the surface mount area, these components pass directly through the solder wave and are joined to the board. This process is followed by a wash and inspection.

3.2.4 Second Operation

In the “second operation” area additional components are soldered by hand. In addition, other hardware and connectors are placed on the board. An operator in this area typically performs all the necessary steps on a board. Most operators are skilled in all the tasks and there is little segregation of the work. Several operators may work on the same lot.

If boards cannot be washed after this step because of the sensitivity of special components, a “no-clean” solder is used that eliminates the need for cleaning. This solder requires a higher skill level and can lead to degradation in quality.

3.2.5 Test

The main goals of the test area are to collect data on manufacturing quality and to capture failures for repair. These tests are typically developed by the customer and use a range of methods from standardized test equipment to custom test fixtures and in-product tests.

3.2.6 Shipping

A final audit of the boards is performed in shipping. From here the boards are either packed in boxes and shipped to the customer or are placed in finished goods inventory.

3.3 Business Systems

A number of business processes are in place to manage the activity in the factory. Planners receive orders, schedule lots and update forecasts in an MRPII system. The purchasing group manages the procurement of all necessary components. The MRP system generates a factory start date for each lot based on manufacturing standard lead times and the customer due date. Standard lead times are the expected time periods for the manufacturing to occur. MRP then calculates the necessary order date for every component based on the factory start date and the component lead time.

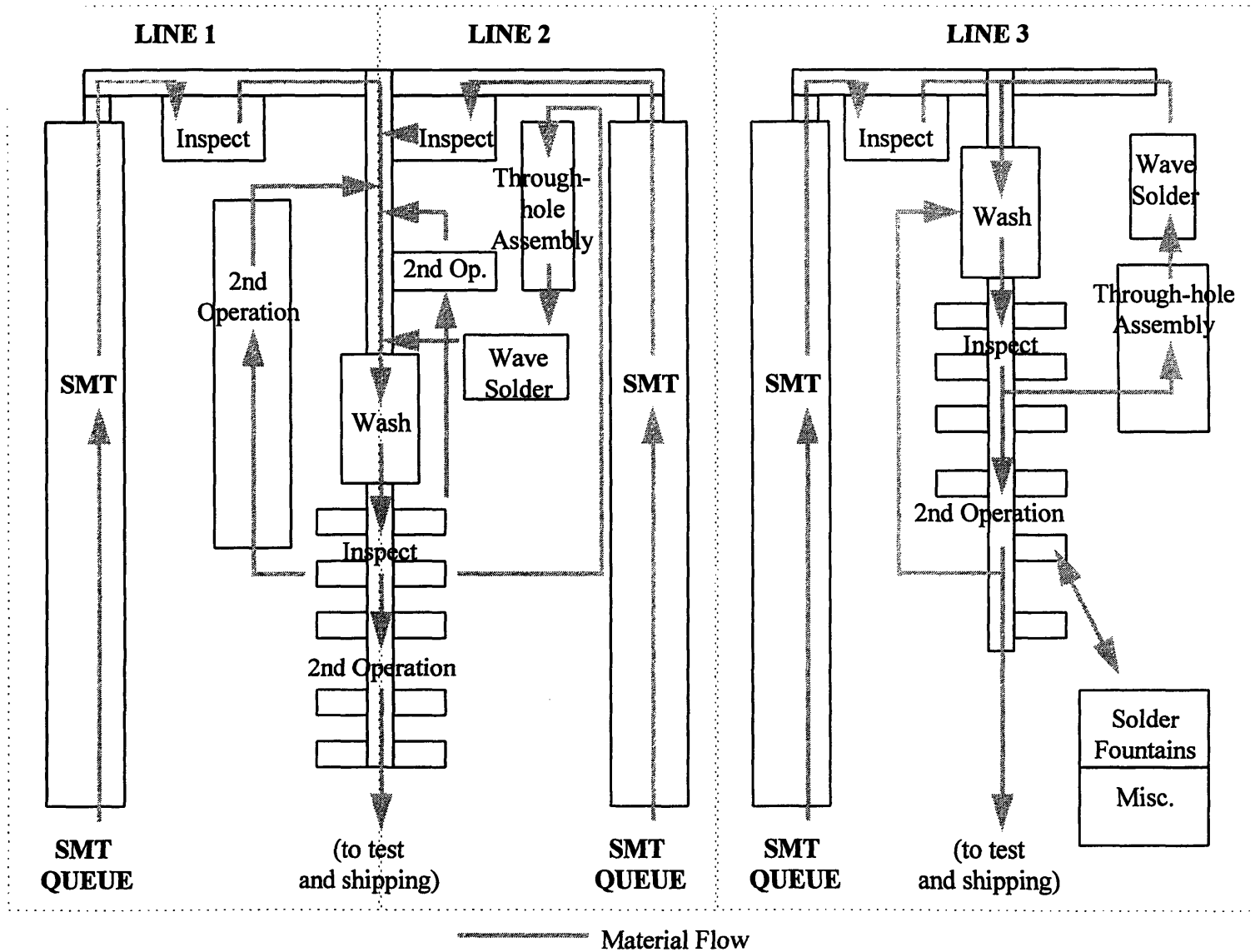
A meeting takes place every morning of factory operation. Planners negotiate with operations supervisors on the release of lots to the factory floor. Typically, lots are released on the MRP specified start date if all components are available. Lots are tracked on the floor by the MRP system. Operators enter data into the system when the lot leaves the workcenter. In addition, an "Order Routing Record" accompanies every lot. This shows the required processes for the product and the expect due date through each process step.

3.4 Factory Organization

3.4.1 Layout

The factory consists of three manufacturing lines, each having a surface mount line and varying levels of through-hole and second operation capability. The kitting and test areas are each their own functional areas. Figure 3-5 illustrates the factory layout.

Figure 3-5: Factory Layout



The Material Control Organization (MCO) contains both the kitting area and the shipping area and is headed by one supervisor. Most of the operators in the kitting area work the second or third shift since the paperwork for jobs released during the morning meeting is not ready until the afternoon.

Line 1 is configured with a surface mount line, no through-hole capability, and a small number of second operation stations. It is staffed fully on first shift and a small team shares time between Line 1 and 2 on the second shift.

Line 2 is configured with a surface mount line, through-hole capability, and no second operation capability. It's staffing is similar to Line 1: Fully staffed on first shift and a shared team on the second shift.

Line 3 is configured with a surface mount line, through-hole capability, and a substantial second operation capability. It is staffed on all three shifts, but most heavily on the first shift.

Lines 1 and 2 are managed under one supervisor, while Line 3 is managed by another. Line supervisors are responsible for the first shift operators on that line and for managing product introductions, forecasting capacity needs, and measuring factory performance. A second shift supervisor manages the operators on the second shift. Any third shift operators report to the first shift supervisors.

The test area is responsible for all testing needs for the factory. It is managed by one supervisor. The area is staffed equally on three shifts with team leaders on the second and third shift. In addition to managing the operators, the test supervisor is responsible for managing test data collection and reporting, customer returns, and new product introductions.

The shipping and finished goods inventory area is managed by the MCO supervisor. A small team works on the first shift. Any products received after the first shift wait until the next business day.

In addition to the operational areas, a process and quality group is headed by one supervisor. In addition to managing the maintenance technicians, process technicians and trainers, he is responsible for overall product quality. Figure 3-6 summarizes CBA1's organizational structure.

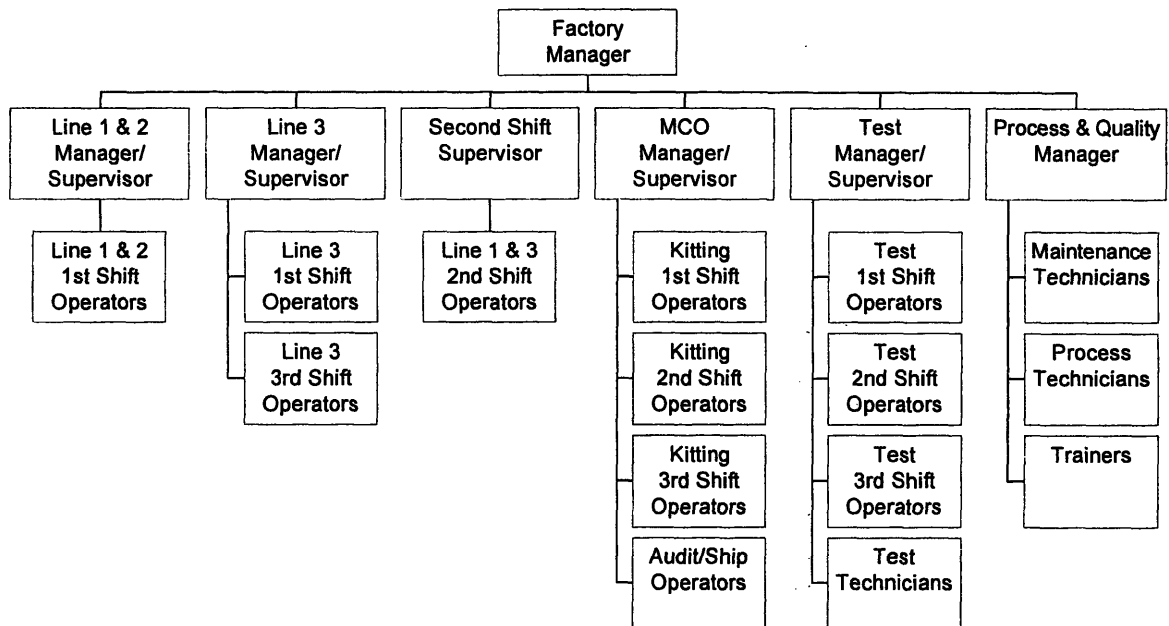


Figure 3-6: Organization Chart (Before Redesign)

3.5 Product

CBA1's product portfolio can best be described as low volume and high mix. In 1996 CBA1 had over 250 active products with individual product volumes ranging from tens of boards to 10,000 boards per year. Board complexity ranges from simple single sided boards with surface mount components and no testing to behemoth boards requiring double sided surface mount, through-hole and a multitude of second operation and test operations.

Age of the product designs is a major factor in the product makeup. Newer products tend to use less through-hole components and are therefore much cheaper to manufacture. Although some older products have been redesigned to take advantage of the cost

savings, many have not because product volumes cannot justify the redesign or FDA re-permitting expenses.

As new products are introduced, they are typically assigned to the manufacturing line which is best configured to manufacture it. Lot sizes are also determined upon introduction. The lot sizes are based on estimated product demand, a cost model, and estimated work content. This cost model includes per lot kitting and planning costs and equipment changeover costs. Effectively, this is an economic order quantity model modified to assure that lot sizes are not extremely large as to be unmanageable in production or to build large inventories of finished goods. The cost model drives lot sizes up in an effort to spread the per lot costs over the larger number of boards in that lot. Lot sizes are limited by the amount of finished goods inventory the lot size would create and the amount of work any one lot would make at a particular process step. For example, a lot size of 10 would be preferred to a lot size of 100 for a product that has a monthly demand of 10 boards. The later would represent 10 months worth of inventory. Also, if each board required 1 hour of second-operation work, a lot size of 100 boards would take 4 operators 25 hours to complete.

4. Analysis

Data for this section was collected by the manufacturing systems already in place. In addition, observational data also contributed to extending the understanding derived from the data. Data is collected on each lot as it passes through the factory. At the end of a week, data can be collected and analyzed. The cycle time data for individual jobs is currently collected in integer days. (i.e. Cycle time of an individual job cannot be 4.3 days. It must either be 4 days or 5 days.)

4.1 Cycle Time Measures

Cycle time can be measured in several ways: The time per job can be captured as lots are shipped, or work-in-progress (WIP) level can be used to indicate the instantaneous cycle time of lots on the floor. This inventory can be measured as the value of the lots, number of boards, or number of lots. Once the time is measured, the cycle time can be reported in several different ways. It can be weight by the value of the job, creating a “dollar cycle time”, or the average amount of time a dollar’s worth of inventory takes move through the system. This may be useful to better understand the impact that cycle time reduction will have on WIP inventory value. If defect rates are fairly consistent across all products, time per lot can be weighted by the number of boards in the job to give an estimate of the time it will take a defect to travel through the system. (Or the time can be weighted by the product’s average defect rate.) This may be useful to understand the impact cycle time will have on quality. In a low volume high mix shop, the number of boards in a lot does not necessarily correlate to the value of the job. Some products have very high component cost, while others have very low cost.

At this circuit board assembly area, cycle time is measured by job and is a simple (unweighted) average. The improvement goals are broad: to improve cost, quality, inventory levels, and service. Some of the lots with the highest cycle time have a low dollar value but very poor quality. (Quality is not equal across all products.) If the cycle time is weighted by the value of this lot, there would be little focus on improving its cycle

time, possibly causing quality to suffer. Alternatively, if lots with low defect rates, high dollar value, and high cycle times are weighted by the defect rate, there would be little focus in improving the cycle time of these products, possibly causing the value of WIP inventory to remain high. These examples are very real as new products typically have higher component costs (and therefore higher board value) but much lower defect rates. Leaving the cycle time measure unweighted provides a happy medium between these and other scenarios.

4.2 Current Cycle Time

Cycle time was typically reported as “8 days”. But reporting just a single number lends little to its understanding. Instead, cycle time is an average of many jobs over a long period, as shown in Figure 4-1. Understanding the distribution around and the contributors to the reported average can lead to discoveries of possible improvements.

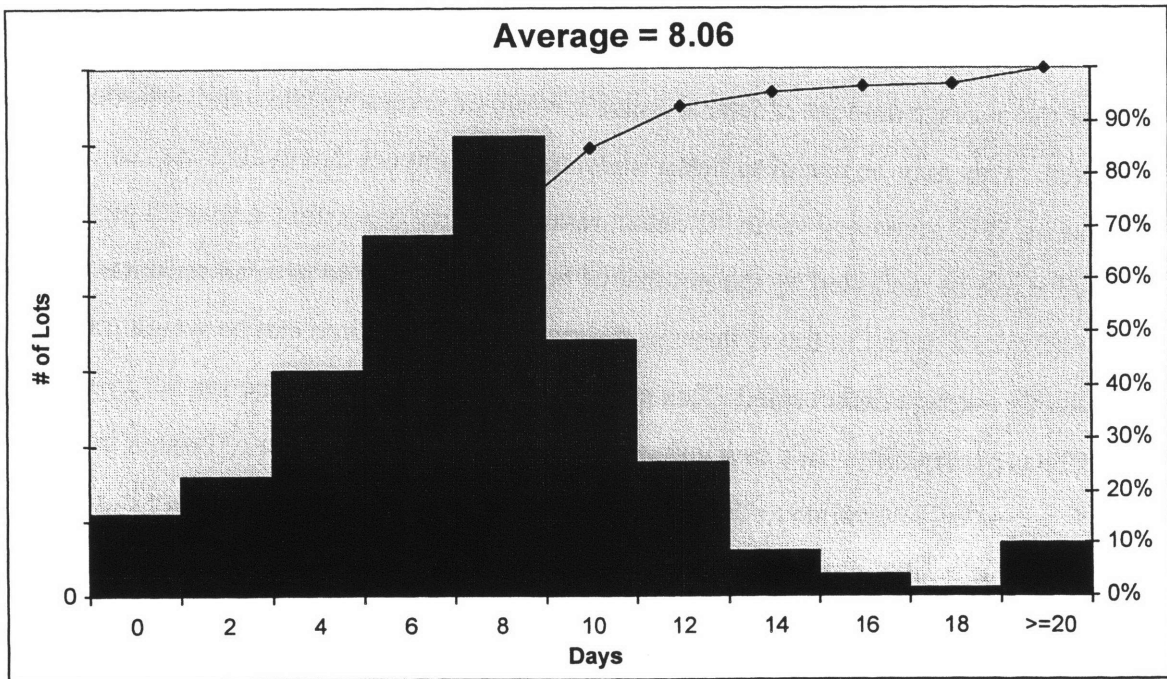


Figure 4-1: July Cycle Time Histogram

This understanding is critical to stopping a desire to increase standard lead times used in the MRP system. For example, it was not well understood why the “Performance to

Manufacturing Due Date” measure was so poor even though the average cycle time was near the standard lead time. This measure tracks the percentage of lots that finish manufacturing by the date specified by the MRP system. Without knowing the distribution, one might expect that if the average cycle time and the average standard lead time are both 8 days, then the measure should be quite high. But the wide distribution of data in Figure 4-1 shows that many of the lots’ cycle times are beyond the average standard lead time. If this was a continuous cycle time measure, the expected Performance to Manufacturing Due Date should be exactly 50% when the average cycle time and average standard lead times are equal. Even with the discrete nature of the data, the measure should still be far below 100% unless it is very tightly distributed. (In this case, it is approximately 60%.)

Prior to this understanding, it was believed that the product could not be built within the standard lead time. While this may be true, this data is not a sufficient indicator.

4.3 Cycle Time Components

4.3.1 Line Analysis

If we wish to improve the factory’s cycle time, we must understand what contributes to it. First, the data is analyzed by manufacturing line to see if there are any clear differences. Figure 4-2 displays the relative volumes (in number of lots) and their cycle time. In addition to having a higher volume, this data shows that Line 3 has a longer cycle time (9.62 days) than Line 1 or 2 (7.21 or 6.86 days). This data also includes kitting, testing, and shipping operations as part of the line. The data can be further analyzed by looking at these components separately.

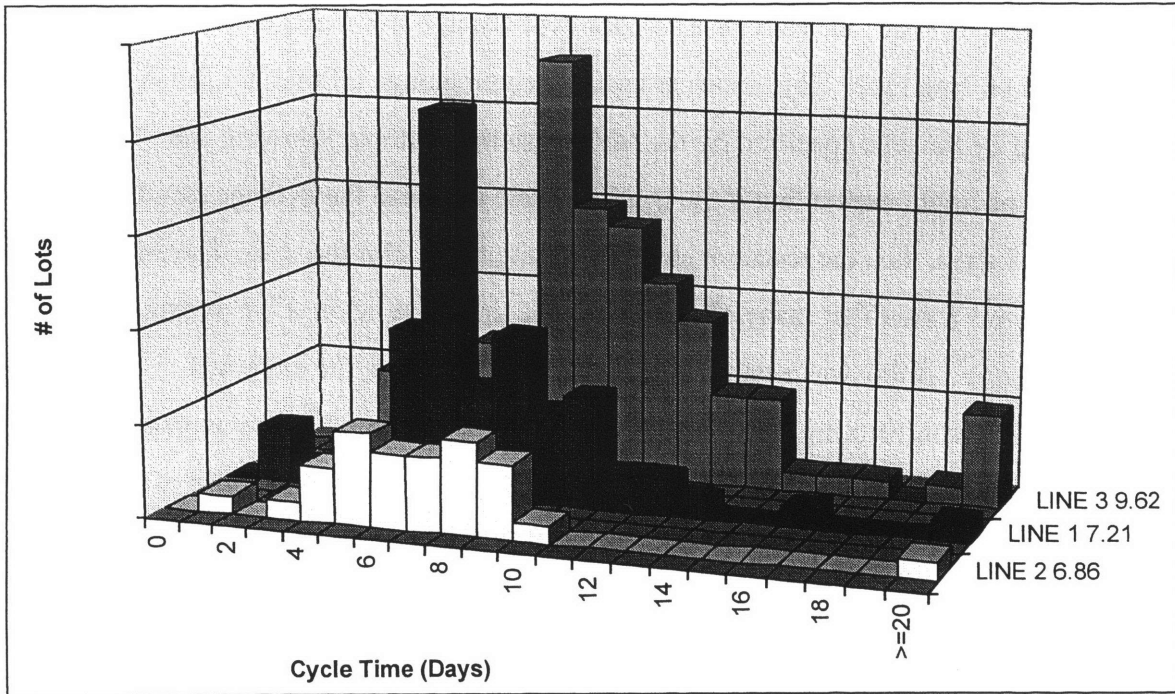


Figure 4-2: July Cycle Time by Line

4.3.2 Functional Area Analysis

The pie chart of Figure 4-3 shows the partial cycle times for each functional area. The slices for Lines 1, 2 and 3 now only include the surface mount, through-hole and second-operation steps performed on that particular line. The kitting, testing, and shipping steps have been separated out from the line data and combined into their own slice of the pie chart. To get a better feel for the impact that these various operations have on the total manufacturing cycle time of the factory, their partial cycle times are weighted by the percentage of the total number of lots that go through each operation. For example, Line 3's measured partial cycle time is 4.92 days. But only 44% of all lots pass through Line 3. Therefore Line 3 effectively contributes 2.16 days to the total average cycle time for the factory. Further, of all the components of the factory's cycle time, Line 3 is 27% of the total.

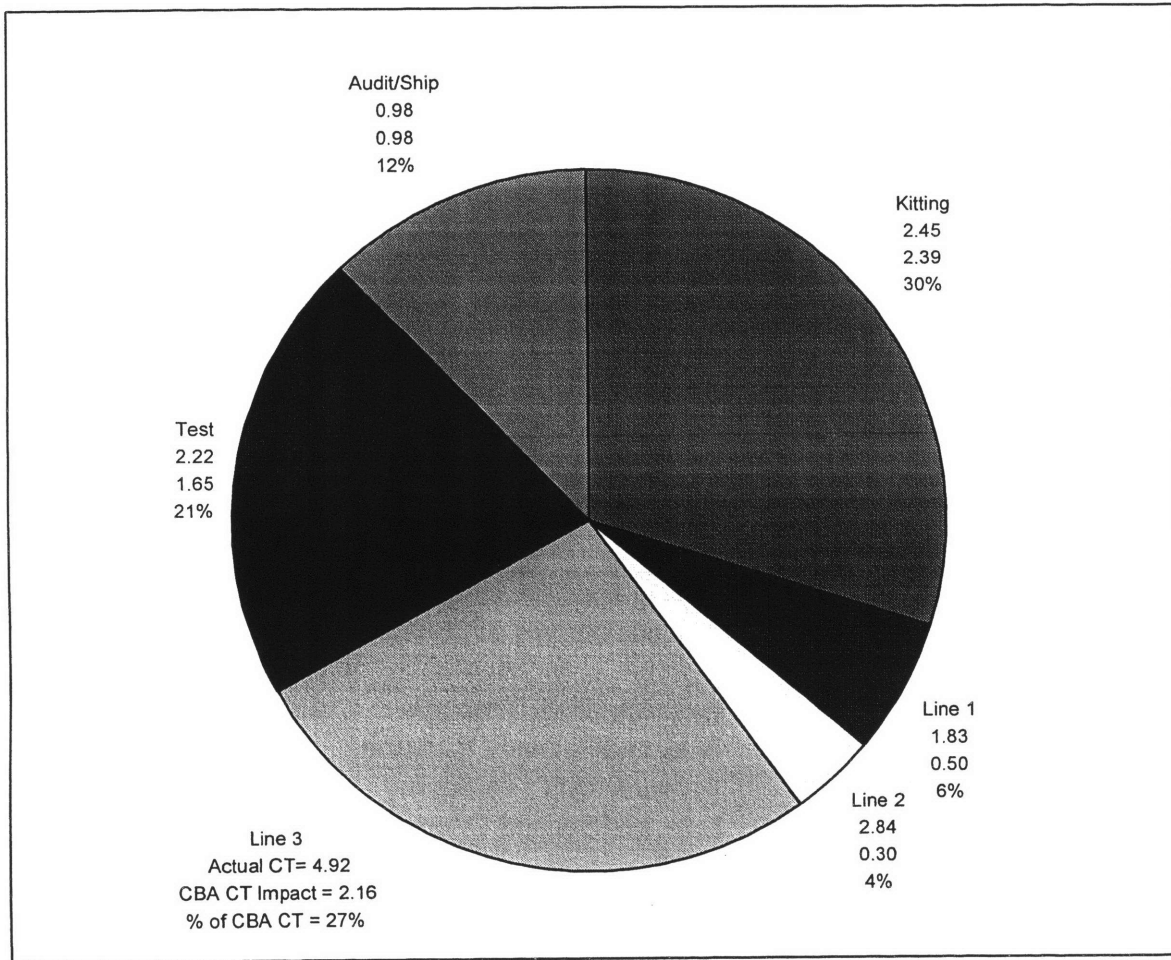


Figure 4-3: July Cycle Time by Functional Area

By calculating the impact of each area on the total cycle time, it is easy to see the biggest contributors and, therefore, the best areas to focus improvement. Even though Line 2 has a fairly large partial cycle time (2.84 days), it has very little impact on the factory's overall cycle time (0.30 days). Cutting Line 2's partial cycle time in half (from 2.84 to 1.42 days) would reduce the factory's cycle time by just 0.15 days. But reducing Line 3's partial cycle time 50% would reduce the factory's cycle time by 1.08 days.

The functional area cycle times are derived from the workcenters that are contained within the operation. Many of these functional areas have more than one workcenter within the area. These workcenters represent either parallel operations where the lot goes through only one of the workcenters, or serial operations where the lot goes through more than one of the operations. Table 4-1 shows which workcenters make up each of the

functional areas and whether the operations are parallel or serial. The process flow diagram in Figure 4-4 further illustrates this. Line 3 is the most complex manufacturing line with six workcenters contained within. Although Lines 1 and 2 have many of the same capabilities, Line 3 has broken out these functions into workcenters. The Test area has two general types of tests, in-circuit and functional, and a “Third Operation”. Product go through no more than one of the in-circuit tests and one of the functional tests. At the Third Operation workcenter, any final work is performed on the product that would have hindered in-circuit testing.

Functional Area	Workcenter Code	Description	Notes
Kitting	WC04	Kitting operations; code depends on type of product	Parallel operations
	WC05		
	WC06		
Line 1	WC10	Includes SMT, Through-hole, and Second Operation	Lines 1, 2 and 3 are parallel
Line 2	WC20	Includes SMT, Through-hole, and Second Operation	
Line 3	WC30	SMT	Serial operations within Line 3
	WC31	Test Point Insert	
	WC32	Back Side SMT	
	WC34	Through-hole	
	WC36	Machine Separate	
	WC38	Second Operation	
Test	WC40	“In-circuit” tests; code depends on type of test equipment	Parallel operations within Test
	WC41		
	WC42		
	WC43		
	WC44	Third Operation	Parallel operations within Test
	WC50	“Functional” tests; code depends on type of test equipment	
	WC51		
	WC52		
	WC53		
	WC55		
Ship	WC99	Audit, Pack, Ship	

Table 4-1: Functional Area Description

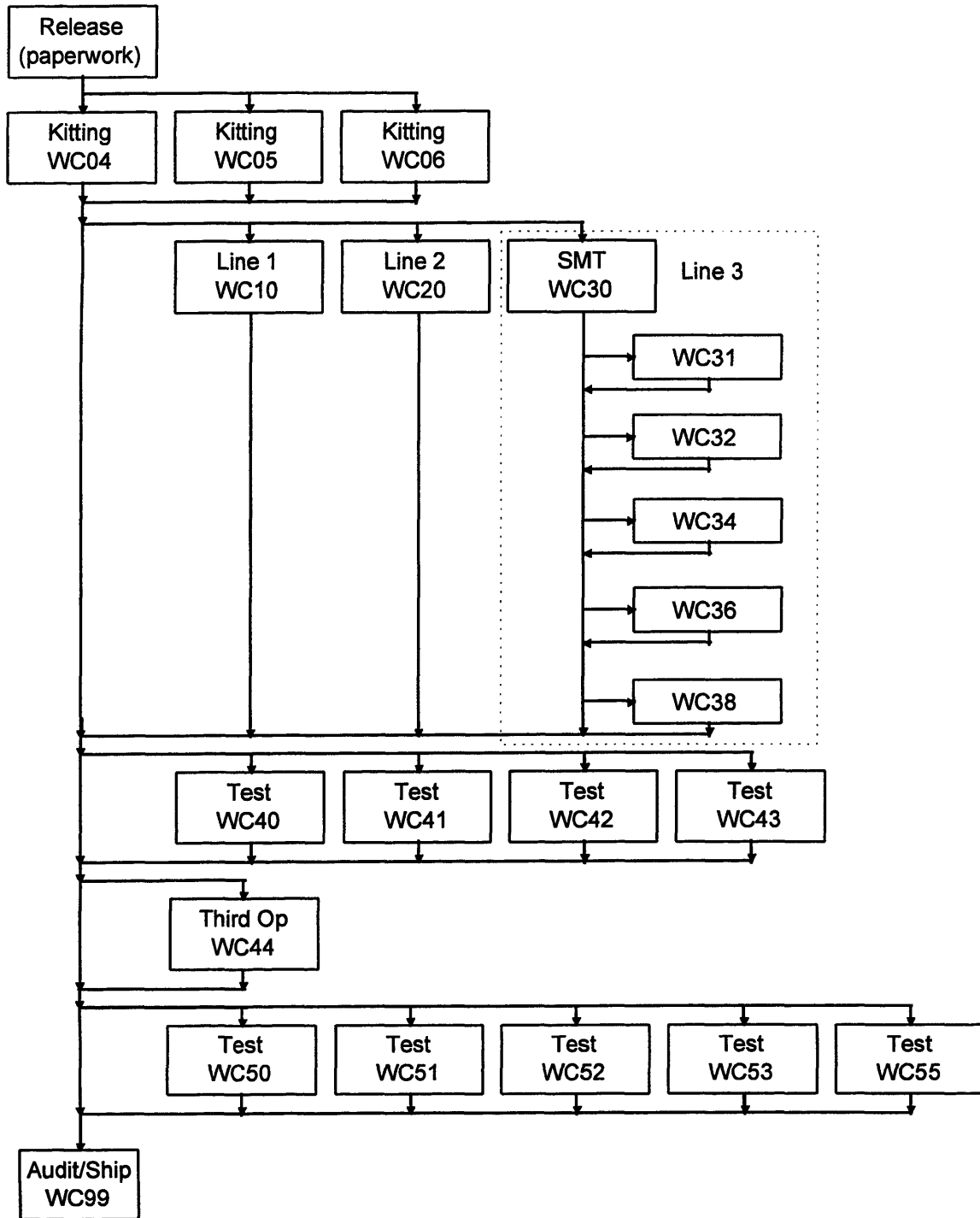


Figure 4-4: Process Flow

Functional area cycle times are a weighted average of all the parallel workcenters within that area combined with the cycle time for all workcenters in series. For example, the workcenters in the kitting area are all parallel operations. These workcenter cycle times

are weighted by the percent of lots that go through that particular kitting workcenter compared to the number of lots that go through all the kitting workcenters. In this case, all lots are only counted once; the sum of the number of lots that go through each of the kitting workcenters is equal to the number of lots that go through kitting.

In some instances, series workcenters are not purely in series. In the case of Line 3 workcenters, the operations occur in the specified order, but some workcenters are skipped. This depends on the needs of the individual product. Line 3's cycle time is also the weighted average of the number of lots that go through each workcenter. But in this case each lot may be counted more than once. The sum of the number of lots that go through each workcenter is greater than the number of lots that go through kitting.

4.3.3 Workcenter Analysis

Data can be analyzed at the workcenter level to gain a better understanding of the contributions to the factory's total cycle time. The data points and right axis in Figure 4-5 indicate the actual cycle time of each workcenter. The bars and the left axis indicate the impact of that workcenter on the total cycle time of the factory.

A workcenter's impact on the factory's cycle time is computed in a similar fashion as the functional area cycle time. The total number of lots that the factory produces is equal to the number of lots that go through shipping (WC99). The workcenter impact is the product of the workcenter's actual cycle time and the fraction of lots that go through that workcenter (number of lots through that workcenter divided by the number of lots through shipping). The sum of all these impacts equals the total cycle time for the factory.

Once each of these impacts are calculated, a pareto of the largest impacts can be created, as shown in Figure 4-5. The workcenters at the left of the pareto have the largest impact on cycle time. For example, cutting the cycle time of WC04 from 2.6 to 1.3 days (50% reduction) would reduce its impact on the total cycle time of the factory from 1.5 to 0.75 days. But cutting the cycle time of WC52 from 2.2 to 1.1 days (again, a 50% reduction)

would only reduce its impact on the total cycle time of the factory from 0.1 to 0.05 days. If these improvements take the same amount of effort, it is more desirable to focus on reducing the cycle time of WC04 instead of WC52.

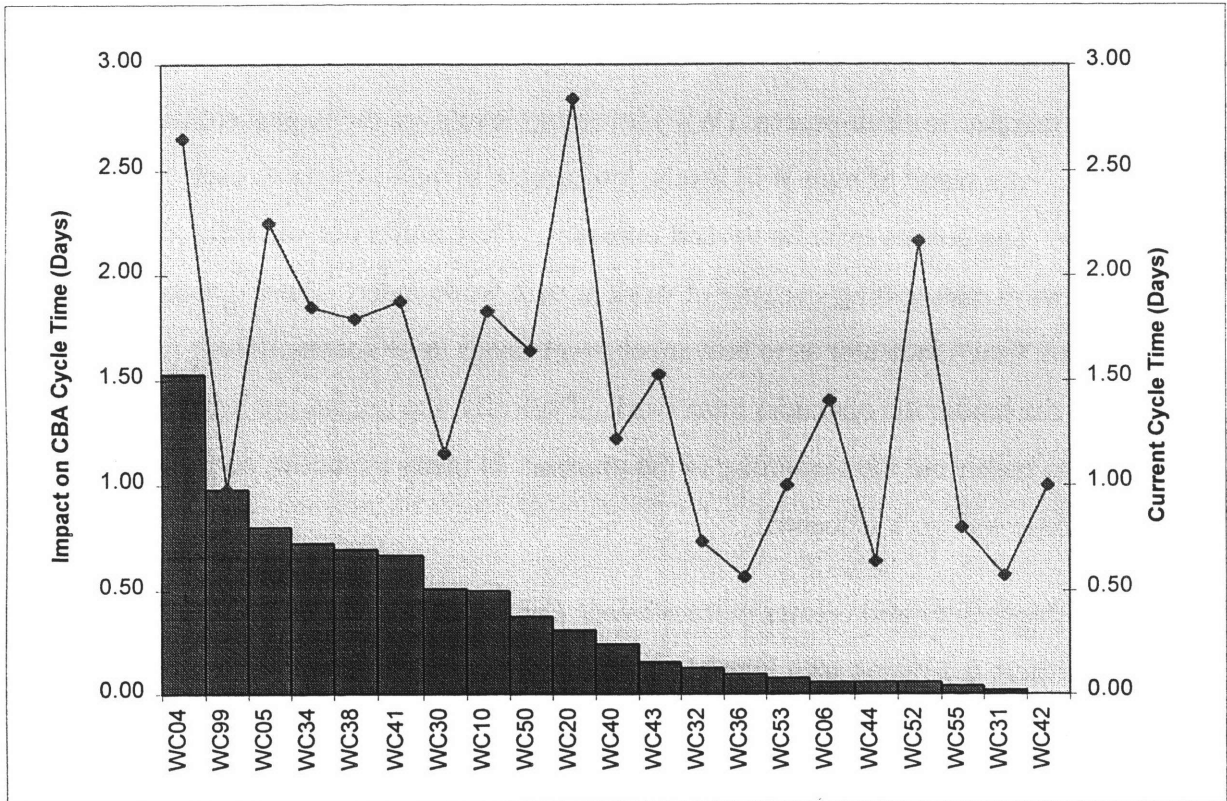


Figure 4-5: July Cycle Time by Workcenter

Once the largest impact items are identified, causes can be investigated. The data indicates that lots are remaining for long periods at the workcenters. Observing the operation typically shows that it takes very little time to actually perform the required processing. Processing times for most workcenters, even with large lot sizes, is on the order of 2 to 4 hours. A large amount of variation is observed to be a function of complexity and lot size. Individual circuit board processing times are typically in the range of just a few minutes. Again, board processing times depend greatly on the complexity of the board and the process step. As the length of time a lot waits at a workcenter is reduced, processing time contributes proportionally more to the total cycle time, warranting an in-depth study of how to reduce processing time.

4.4 Results

The combination of data analysis and observation leads to several conclusions about the major causes of the current cycle time.

4.4.1 Queues

By a wide margin, work-in-process (WIP) inventory levels are the largest contributor to cycle time. As a result of high WIP levels, lots remain in queues prior to each workcenter. The queues exist for several purposes. They buffer out variability in the process, always maintaining a supply of work at each workcenter. These queues also function as a visual indicator as to how much work needs to be accomplished; the bigger the queue, the harder the operators must work. Typically, the queues are larger than necessary to buffer out the variability in the process. In many instances, operators can move to where the work is located.

Having multiple lines also creates more queues. For example, prior to each surface mount line there is a queue with kitted lots waiting to run on the line. Since products are defined to run on only one particular line, these three queues are necessary to feed each line. If the three lines were identical, giving the flexibility of any product running on any line, only one queue would be needed.

Processing of work in the queues is sometimes inefficient. Deciding which lot should be processed next often requires examining all the lots in the queue to see which has the highest priority according to the workcenter due date. In some workcenters, more than one lot is processed at a time. This creates a longer average cycle time than if only one lot is processed at a time. For example, two lots arrive simultaneously to a workcenter with two operators. Each lot requires two hours of work: either two hours for one operator or one hour for two operators. If both lots are worked on simultaneously, both lots will be completed in two hours, resulting in an average cycle time of two hours. But if the operators team up, working on one lot at a time, the first lot will be completed in one hour and the second lot will be completed one additional hour after that, resulting in

an average cycle time of 1.5 hours. In addition to reducing the cycle time, the work moves between workcenters in a more continuous manner, reducing the clumpiness of arriving work at the next workcenter.

4.4.2 Lot Sizes

In a batched operation such as this factory, a lot does not move to the next workcenter until every board in the lot has received the necessary processing. A result of this is that larger lot sizes mean all the boards in the lot wait longer to move to the next workcenter.⁹

Large lot sizes also increase the amount of WIP and finished goods inventory.

Inventories tie up cash and are expensive to manage. The inventories also represent a risk: if a design is changed or defects detected, some of the materials may need to be scrapped.

4.4.3 Product

Poorly designed products often require special handling and additional manufacturing steps. Often these products were designed prior to the introduction of newer technologies, but these products for one reason or another have not been redesigned. In CBA1, many new products are designed to only need surface mount assembly. This greatly improves the cycle time because now many of the time consuming manual operations have been eliminated.

4.4.4 Efficiency and Capacity

Efficiency is most important at the bottleneck of the factory. A factory can only produce at the rate which the bottleneck process step can produce. If capacity is limited, efficiency is crucial. A bottleneck will create a queue of work ahead of it, costing cycle time.

⁹ Karmarkar, "Lot-sizing and Sequencing Delays", *Management Science*, March, 1987, p. 419.

Efficiency is important at the non-bottleneck process steps from the standpoint of how long it will take to get products from release to the bottleneck or from the bottleneck to the customer. If four hours of process time is required prior to the bottleneck, the lot must be release at least four hours ahead of when capacity will be available at the bottleneck. If that process time is cut to two hours, then the lot can be released as little as two hours ahead. Once the lot has completed processing at the bottleneck, only the time required to perform the remaining process steps limits the cycle time.

4.4.5 Environment

Finally, the environment which this factory lies is key to the cycle time. The high mix and low volume business necessitates relatively short run lengths with many equipment change-overs.

5. Continuous Improvement

With a new understanding of the components of the manufacturing cycle time, improvement efforts began. Since queuing and high WIP inventories are the largest contributors to the cycle time, this was the focus of improvement. Effort was concentrated mostly on Line 3 and Kitting operations as these areas contributed the most to the cycle time. But other improvements were also targeted to help factory-wide. Most of these efforts discussed in this section were done in parallel, resulting in a reduction of the factory's manufacturing cycle time from 8 to 5.2 days and reducing Line 3's cycle time from 8.6 days to 4.9 days.

5.1 Visual

Line 3 has several workcenters and its associated queue. A visual tool was created to place more focus on cycle time. Numbers were placed on every lot on the manufacturing line indicating the number of days it had been on the floor. This has two uses: It helps the operators prioritize on which jobs to work and it shows management how much WIP is on the floor.

For optimal cycle time alone, the lot with the shortest actual processing time remaining should be built first¹⁰. But since the goal is not cycle time alone, the jobs with the highest number (i.e. had been on the floor the longest) were worked on first to ensure good customer service. This has the effect of creating a first-in first-out (FIFO) sequencing algorithm while placing priority on any lot that may have been held up for various problems. It also pulls lots from the back end of the process.

Operators were empowered to move to the workcenter where the highest priority work was located. This movement showed both where the bottleneck of the line was located and

¹⁰ Baker, Introduction to Sequencing and Scheduling, p. 18.

what skills were the most in demand. If operators were not skilled in the needed workcenter, training was provided.

As WIP inventory levels and cycle time came down, the numbering system was converted from tracking number of days to tracking number of shifts. Operators recorded and graphed the number of lots and the average amount of time required to build those lots. The counting of the cycle time on the line started when the lot was started on the surface mount line. This created an incentive for the surface mount line to only build lots when the receiving workcenters had capacity available. The ultimate effect of the system was to move the WIP in the queues on the line to the queue prior to the surface mount line and the kitting area.

5.2 CONWIP

Now that WIP was removed from the line itself, it became clear that jobs were being released before capacity was available to build them. At times, released lots would sit in the surface mount queue for two days before processing began. This demonstrated the weakness of the MRP release system. This method is to release jobs when MRP desired. MRP's release dates are simply a calculation of the necessary start date based only on the customer due date and the standard lead time. Capacity or WIP levels do not factor into the release mechanics.

A pull system called CONWIP (constant WIP) was created to help manage the releases. A CONWIP caps the amount of work (in process and in queue) on the line¹¹. This is similar to just-in-time (JIT) which fixes the amount at a process step and its queue, but it extends this to the entire line. The system tracked the amount of manual work in line prior to and including the manual operations (through-hole and second operation), as this is the bottleneck of the lines. The desired WIP level is calculated from the demonstrated throughput of the bottleneck multiplied by the amount of time necessary to do all the

¹¹ Wallace and Spearman, Factory Physics, Foundations of Manufacturing Management, p. 323.

operations leading up to the bottleneck and some safety stock level to cover variability in output of the bottleneck and delays in the operations. For example, if the throughput of the bottleneck is 2400 minutes of work per day and it takes a minimum of 1 day for a job to get from release through kitting and surface mount, a minimum of 2400 minutes of work must be in line at all times. Since releases are made only once per day, enough jobs must be released to cover that full day plus the day to get to the bottleneck. This creates a minimum WIP level of 4800 minutes of work for the bottleneck. Much additional time is added to cover variability. A CONWIP system is set up for each of the three lines.

While this calculation is important, variability is difficult to measure. Instead of relying on this calculation to set the WIP level, it is used to understand how much of the WIP is necessary because of the length of processing and how much is necessary because of variability. Gradually, the CONWIP level is reduced. If the bottleneck becomes starved, the WIP level cannot be reduced further. If, for example, the WIP level is equal to four days of work but it theoretically takes two days to get to the bottleneck (one day of work and one day to cover the full release day), the other two days must be due to variability. As causes of variability are reduced and eliminated, the CONWIP level can be further reduced.

As the variability is reduced, the processing time and release timing become more significant. Enough work must be released to cover the time period to the next release. If releases are made just once per day, a full days work must be released to cover the time. If release could be made twice per day, only a half day of work needs to be released. In addition, since the amount of time for this work to reach the bottleneck has been reduced by a half day, the time period for which safety stock must cover the variability is reduced. With more releases per day, the factory can more quickly respond to variability so less safety stock is necessary.

Next, processing time is examined for ways to better streamline the process of moving the work from release to the bottleneck most rapidly. As these three areas (variability, releases, and processing time) continue to be improved, the CONWIP levels continue to

be reduced. CONWIP creates a pull system, only releasing work when capacity is available. This works in conjunction with the MRP system which prioritizes orders and calculates estimated start dates. If the factory begins to fall behind these estimated start dates, overtime must be worked or more capacity added.

5.3 Standard Lead Time Reduction

MRP uses “standard lead times” to calculate release dates based on due dates. In the past, lead times were often increased because what was often stated as “the work cannot be completed in the given time, so increase the standard lead time.” While this does allow manufacturing more time to complete the work on the floor, it also releases more work onto the floor, increasing WIP levels and the efforts required to manage it. This material is not being worked on; it is just sitting in queues. This creates a vicious cycle: As standard lead times increase, efficiency declines and the perception is created that there is not enough time to do the work, leading back to the desire to increase the standard lead times. But this cycle can be broken by including in the standard lead times only the amount of time necessary to do the process steps with some amount of safety. Once it is realized how destructive this cycle is, it can be managed by restraining the desired increases. In fact, as WIP levels are reduced, standard lead times should be reduced so that MRP more accurately generates desired start dates. These standard lead times can be reduced until they match the actual processing time for the job.

5.4 Intra-workcenter Variability

More emphasis was placed on operators working as teams on each job. Instead of each operator working on a different job, as was the previous method, they began to team up. This has the effect of more rapidly completing one job while keeping all other jobs in the queue. This more evenly broke the duration between completed lots, smoothing the flow to the next operation. This reduction in variability translates into a reduction of needed safety stock. In addition, with all jobs being processed through a workcenter serially, jobs are pulled out of the queue more smoothly.

6. Factory Redesign

As continuous improvement efforts proceeded, it became clear that the current design of the factory would ultimately limit reaching the long-term cycle time goals. The greatest benefit of the analysis and continuous improvement prior to redesign is the gain in understanding of the purpose of cycle time improvement and the current problems. With this knowledge, a team consisting of representatives from manufacturing, engineering, facilities, systems, planning, finance and management worked together to define the improvements necessary for the factory.

6.1 Redesign Process

The redesign effort was kicked off with a full day off-site meeting with all team members. The morning was spent in a simulation game of the current manufacturing environment and a then of a new, improved manufacturing environment. The simulation, involving Legos and Monopoly money, demonstrates the value of cycle time improvements. When jobs are released to the manufacturing team, component suppliers are paid. When orders are shipped to the customers, payment is received. Employees are paid daily. In the first simulation, queues exist between each workcenter and lots cannot be shipped to the next workcenter until the lot is completely finished at that workcenter. Jobs are released by a predefined schedule. Defects are introduced into the production but are not detected until the testing step near the end of the process. A hot job is also introduced. Inventory, cash-on-hand, cycle time, and cost of quality are tracked.

In the second simulation, queues are eliminated and individual units of production can be transferred between workcenters. Jobs are released only to maintain a small queue prior to the first workcenter. Again, inventory, cash, cycle time, and cost of quality are tracked. After playing each simulation for several “days”, differences are discussed.

In the second simulation cash-on-hand is much higher since very little is tied up in WIP inventories. Defects are more quickly detected, contained and corrected, saving repair

costs. Hot jobs move rapidly through the system and require little extra effort in the factory. In contrast, there is very little cash-on-hand in the first simulation as most of it is tied up in WIP inventory. Many of the same defects are created before the problem is detected and corrected. While hot jobs move quickly through the system, extra effort is needed.

But in order to make the second simulation work, operators must be able to move to the work. In order to do that, they must have a diverse set of skills. Surface mount lines must be matched. Variability in all process steps must be eliminated. Rules about releasing work and transfer of lots between workcenters must be relaxed. The group agreed that a redesign was necessary and would provide opportunities for improvements in cycle time, quality, and inventory levels.

The remainder of the day was spent brainstorming on all the areas of the factory that needed to be considered for the redesign. Once a list was created, groupings were made and assigned to the appropriate individuals or teams of individuals. A tentative schedule was created. Following the off-site meeting, weekly meetings were held to work on the redesign.

6.2 *Factory Layout*

The new factory layout is shown in Figure 6-1. The layout has been developed not just to optimize cycle time, but to improve costs and quality as well. Major differences are discussed below.

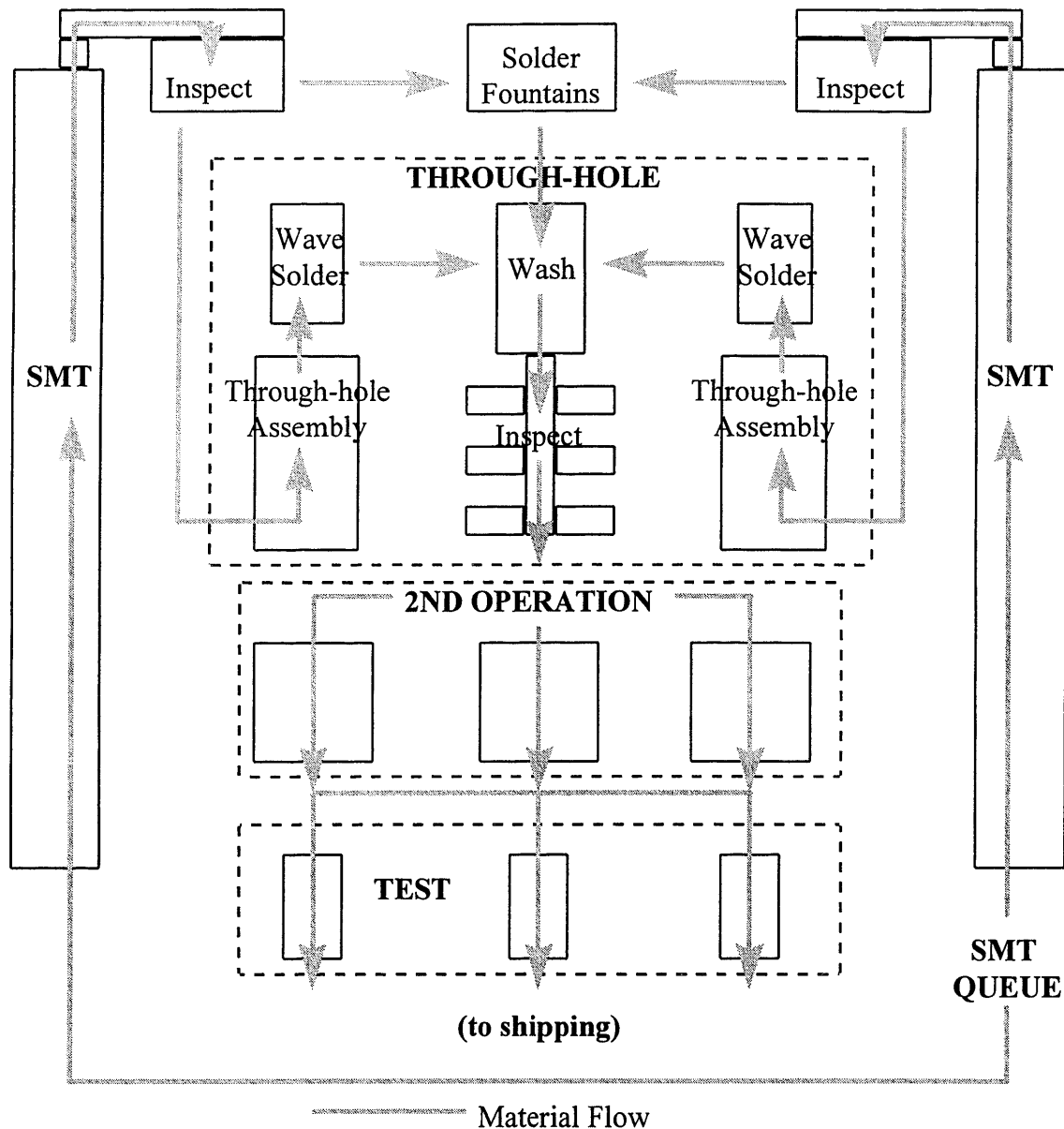


Figure 6-1: Redesigned Factory Layout

6.2.1 Flow and Bottleneck

The vision for the new factory design is that boards will smoothly flow through the factory. While the tail end of a job is being built on the surface mount line, test data will be available from the first boards in that same lot. Instead of waiting for a lot to complete one workcenter before moving to the next workcenter, enough capacity will exist to assure that boards can be pulled from the surface mount lines as soon as they have been

inspected. This eliminates the need for large queues between many of the workcenters. Some small queues will still be needed since the complexity of boards (and therefore the amount of work needed to build the board) varies widely. These queues will provide a small buffer if, for example, through-hole is working on a difficult lot while surface mount is working on a simpler product.

A conscious effort is being made to make the surface mount lines the bottleneck of the factory. Having the bottleneck at surface mount eases the management of the CONWIP release method. The CONWIP will cap WIP up to surface mount area. Since this is early in the process, the period for which variability must be buffered is reduced.

Another benefit to placing the bottleneck at surface mount is that it increases the speed at which defects are discovered. Prior to surface mount, no defects are created because nothing has been permanently built. After the bottleneck, products flow rapidly all the way to test. If defects are created anywhere in the process, from surface mount through second operation, they will be quickly detected at test. If the bottleneck is after surface mount but before test, the queue at the bottleneck would create a significant delay in the time it takes a board to get from surface mount to test. This would slow down the detection of defects created at surface mount.

Finally, the surface mount equipment is the most capital intensive piece of the manufacturing process. Adding additional capacity is expensive. As the bottleneck, focus is maintained on surface mount to improve utilization and reduce setup time.

If surface mount is the bottleneck, then, by definition, all other areas have more capacity than surface mount. Production mix is shifting to products which use relatively less of the manual operations. At the same time, lot sizes will be reduced. The reduction of lot sizes will increase the number of setups performed, consuming more capacity. Setups at surface mount are much larger than other areas. Thus, reducing lot sizes will more quickly consume surface mount capacity. As these two things happen over the coming months, surface mount will become the bottleneck.

6.2.2 Three-Shift Operation

The factory went from a shift structure that had most of the operators working on the first shift to a balanced three-shift operation. The purpose of this is to create an environment where the work flows consistently around the clock. In the old design, even though the test area worked three shifts, the lines worked mostly on the first shift. The effect of this is a build-up of work in the test queues during the first shift and then test would clear out the queues on the second and third shift. Going to a three-shift operation will remove some of this queuing. Another advantage to three-shift operation is the reduction in the number of operators on the floor at any one time. This reduction improves the efficiency of the employees and the workcenters. In the through-hole operation, with high staffing levels some products can be built more rapidly than the wave solder machine can run. Reducing the staffing eliminates an environment where the operators slow to the rate of the machine.

6.2.3 Surface Mount

The number of surface mount lines were reduced from three to two. These lines will be matched so that any product can be run on either line. This simplifies the tasks of releasing work and kitting. In the old design, releases had to be managed for all three lines. This required monitoring the WIP level and negotiating releases for each line. With identical lines, the effort to manage releases is reduced to effectively one line. Safety stock necessary to cover the variability of the lines is greatly reduced because both lines will share the same queue.

The elimination of one of the lines and the more efficient use of floor space due to three-shift operation opens up additional floor space. This floor space will be used to pilot new technology. Had this space not been available, CBA1 would have incurred additional costs to pilot the new technology.

Value is placed on the surface mount line operators communicating with the through-hole, second op and test workcenters. This would aid in maintaining a good flow of

products through the factory and quick communication of needs and problems. In one design option, the two surface mount lines were placed side-by-side. While this would have aided in the surface mount lines working together, this would not encourage the desired communications. Instead, the two surface mount lines were separated and the other workcenters were placed between them, creating more contact between all workcenters.

The downside of this design is that the two surface mount lines would not be able to share ideas and work together as easily. To compensate, a single workcenter approach (both surface mount lines are treated as one workcenter) is being taken. Rotations will be set up to ensure that operators will have contact with all other operators. Management of the surface mount operators will fall under one supervisor to create an environment where resources can be moved quickly between lines.

6.2.4 Wash Elimination

The basic process flow has been altered to eliminate some of the washing steps. In the old factory design, boards were washed after every soldering step. But the new design was created to easily skip the wash step after the surface mount lines if they would be washed after through-hole operation. This wash step can be skipped as long as the boards are washed with 24 hours of the application of solder. With a cycle time goal of one day for the whole process, this is expected to be easily met.

6.2.5 Through-hole

The layout of the through-hole workcenter is such that through-hole inspectors are situated next to the through-hole operators. This layout disrupts a continuous flow that is desirable if only cycle time is considered. But since quality is an important factor in the redesign, this trade-off is considered very important.

6.2.6 Second Operation

Second operation benches, where many of the manual work is performed, are situated so that operators can share work and learn from each other. Prior to redesign, the arrangement of benches required that operators had to get up from their benches if they needed assistance from someone else. Washing after second operation will be eliminated by using a solder that does not require washing.

The solder fountains are typically used when wave soldering is not possible. In this case, boards must be washed after the fountain. Although solder fountains are part of second operation, they are located near the surface mount inspection stations prior to the washer. This location maintains a smooth flow from surface mount inspection to the fountains, then through the washer to be finished up at second operation.

6.2.7 Test

The “in-circuit” testers will be located just below the second operation area. These testers give the most rapid and accurate feedback on the quality of the products coming off the line. Both the smoothing of the flow to the testers from a three-shift operation and the addition of test capacity will assure that no queue builds up before this step. As test data comes available, the location of the testers facilitates direct communication of problems back to area that caused them.

6.2.8 Other

The router and test point insertion machines will not be located within the new flow as there are used by only a few products. Instead, these products are being phased out or redesign to eliminate the need for this equipment. The equipment will still be available, but the location is inconvenient to facilitate a continuous flow. Although products which use this equipment will suffer longer cycle times, the cycle time of all other products will benefit.

6.3 Organization

To better align with the new factory layout, the organizational structure was re-examined. First, running a level three-shift operation will require more supervisors on the second and third shifts and less on the first shift. The interface between the kitting and surface mount workcenters is considered essential to the performance of the new factory. When surface mount is the bottleneck, it will be important to maintain close relationship between these two areas to manage the queue between them and to assure the optimization of the surface mount lines. Many opportunities exist for kitting operators to help reduce setup time and eliminate kitting problems that effect the surface mount lines. Therefore, the factory will be divided after the surface mount operation into front-end and back-end groups. The new organizational chart is shown in Figure 6-2.

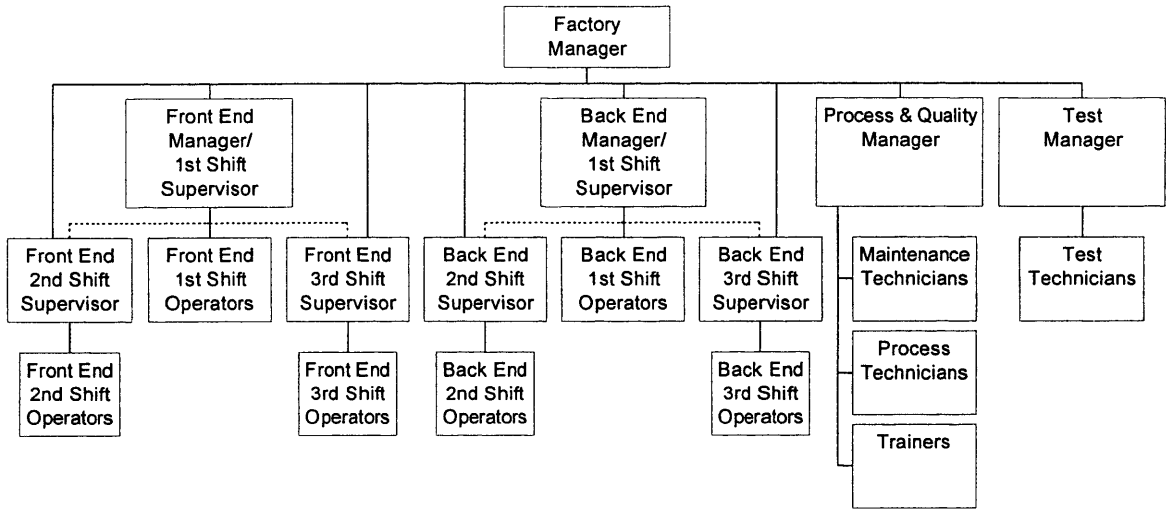


Figure 6-2: Organization Chart (After Redesign)

Front end supervisors will have the responsibility to manage the operators on their shift that work at kitting, surface mount, and shipping. Back end supervisors will manage operators at through-hole, second operation, and test. First shift supervisors will have additional responsibilities to manage the business aspects, engineering efforts, new product introductions, and coordination between shifts. The second and third shift supervisors will be managed by the factory manager, but will maintain a dotted line reporting structure to the first shift supervisor/managers. All supervisors will be

responsible for managing factory priorities, WIP inventory and work releases. The test manager, with a team of test technicians, will manage the maintenance and sustaining of test equipment and test programs, new product introductions, customer returns, and quality feedback.

6.4 Post-redesign Improvements

It is important to note that once the redesign is complete, the cycle time will not magically be reduced or quality levels increased. Instead, the redesign will create opportunities for further improvements to be made. These improvements could not be made as easily in the old design. After the redesign is completed and WIP levels are reduced, many new problems will be visible. These new problems will require more continuous improvement to resolve. As problems are removed, WIP levels and standard lead times can be reduced so that cycle time reaches the desired levels. These projects, although not essential to making the rearrangement itself successful, will need a high level of focus throughout the year following the physical rearrangement of equipment to ensure the full benefits are derived from the new design.

Large lot sizes tie up machines and workcenters, causing the buildup of queues. Reducing lot sizes at first reduces this problem, but eventually causes the total work load at the workcenter to increase because of the increased number of setups.¹² Through a combination of efforts, these queuing delays can be minimized and throughput can be maximized, while meeting demand. Reduction of the time to perform a setup can alleviate some of this problem by turning unproductive capacity into productive capacity. Coordination of release of lots through optimal sequencing and timing will also reduce

¹² Karmarkar, Kekre, Kekre, "Lotsizing in Multi-Item Multi-Machine Jobs Shops", *IIE Transactions*, September 1985, p. 291.

some of the delays. Finally, product heterogeneity can greatly impact queuing and cycle time.¹³

6.4.1 Lot Sizing

The ideal factory would produce daily exactly what each of its customers demand for that day. Minimal finished goods inventory would be maintained to cover uncertainty in demand and quality. Quality feedback from customers would be immediate since finished goods will be consumed the day after they are produced. Unfortunately, to meet this ideal, CBA1 would have to produce most of the 250 products every day, requiring the average build time, including setup, for each days demand for each product to be less than 12 minutes.¹⁴ Considering current setup times alone are well over 12 minutes, lot sizes and associated schedules must be chosen to optimize the available capacity while meeting customer demand, reducing cost, and improving quality. As setup times are reduced, the factory can move closer to this ideal. As discussed earlier, reducing inventory also reduces cost.

Additional complications in lot sizing include wide variance in work content at each workcenter, cost of raw materials and finished goods, and demand. Board complexity ranges from simple one-sided surface mount boards with no manual content to mammoth double-sided surface mount boards with a high manual content. Component costs vary from just a few dollars to a few thousand dollars. Demand ranges from a few boards per month to several thousand per month.

Given this complexity, choosing lot sizes is not a simple task. As surface mount capacity is most critical and most difficult to add, the processing time for the lot at surface mount should be used as a constraint. Since the ratio of surface mount to manual work content varies widely between products, the amount of work at the manual workcenters will shift

¹³ Karmarkar, "Lot Sizes, Lead Times and In-process Inventories", *Management Science*, March 1987, p. 411.

¹⁴ $(2 \text{ SMT lines}) \times (1440 \text{ minutes per day}) / (250 \text{ product}) = 11.52 \text{ minutes.}$

significantly from product to product. Training of through-hole and second operation operators will add flexibility to these areas to meet swings in demand for varying skill sets. But some products still require many minutes of work per board. A large lot size would clog the manufacturing floor. So this must be a loose constraint to assure that these manual areas are not overwhelmed. Other constraints include the dollar value of inventory created by the lot size and the duration that the finished goods inventory will last. An inventory value constraint will keep a cap on the inventory costs. Reducing the duration of inventory will reduce the delay before receiving quality data from customers.

In addition to cycle time, lot sizing also impacts financial planning. Both monthly, quarterly and yearly financial performance is forecasted. Large lot sizes (and their associated high total value) create a problem where the manufacturing operation misses a monthly goal which is followed by beating the next month's goal. Since many factories try to draw information from the shape of the revenue curve, this effect may produce a false message. Smaller lot sizes would reduce the impact that a single lot would have on financial performance.

6.4.2 Setup Time Reduction

Reducing the average lot size will require more setups to be performed. To maintain the same throughput, setup time must be reduced. Areas of exploration include creating permanent setups; concurrent setups while a machine is still running; and using pit crews, similar to those used in auto racing, to reduce the setup times.

Some analysis has been performed on having certain components permanently installed on some of the machines or on feeders. Tradeoffs exist in capital costs and inventory costs versus handling and setup costs, quality improvements, and setup time improvements. Analysis determined for each component whether it was worth the capital expense of purchasing a feeder. The conclusions drawn from the analysis are that more feeders should not be purchased, but as many of the currently owned feeders should be

converted to permanent setups. The pay-back on the capital was several years, while the pay-back on the extra inventory required was very short.

With the two surface mount lines performing as a single team and the kitting operators under the same supervisor, the possibility of creating a pit crew may improve setup times. A change-over team can focus on setting up the next job as soon as one job is complete.

Other opportunities exist to do some tasks while the machines are running another job. Currently, components can be set up on the machine while it is running another job. But verification of the setup cannot be performed until the machine is stopped. Re-examining this and other areas like it may show some opportunities for reduction. Possibilities include automating the verification, doing it off-line, making it more efficient, or eliminating it.

6.4.3 Production Scheduling and Sequencing

Cycle time can be further optimized by releasing the proper amount of work. If too much work is released cycle times will rise. But the danger of too little work is that the bottleneck capacity will be used inefficiently. The amount of work that should be released to production is equal to the demonstrated capacity plus a “safety” amount to cover the expected variation over the period between releases minus the amount remaining from the previous period. The amount to cover the variation can be quite significant. The most effective way to reduce this variability is to reduce the time period itself.¹⁵ Thus, increasing the number of releases per day will allow the safety level to be greatly reduced. To make this feasible, the release methods must be re-engineered to reduce dependence on the planning organization and supervisors and to reduce the delays from the decision to release to the time the material is available for production. An automated tool can be developed to improve this process.

¹⁵ Groenevelt and Karmarkar, “A Dynamic Kanban System Case Study”, Production and Inventory Management Journal, Second Quarter, 1988, p. 48.

With the wide product mix, job sequencing becomes very important. An optimal ordering, for example, might be to immediately follow a job with high manual content with a job with very little manual content to keep queuing throughout the factory to a minimum. Also, setup time may be reduced between lots if some economies exist in running similar products together.

6.4.4 Processing Time

Processing time at several workcenters is lengthy. The kitting time, including paperwork delays, can take up to 6 hours. If this and other processing times are reduced, cycle time will also be reduced. Other areas of improvement include building hardware sub-assemblies for products in parallel with board assembly, greater use of team work to reduce the cycle time of each workcenter (work on all jobs serially), and elimination of non-value-added processing.

6.4.5 Product Design for Manufacturability

Many opportunities exist to improve the product designs to help reduce cycle time. Reduction of the use of through-hole and other manually soldered devices will greatly reduce the cycle time and improve quality. Many boards can be redesigned to incorporate known fixes for quality problems, as these problems contribute to the cycle time.

Component standardization will reduce the amount of inventory that must be managed and simplify setups. Component standardization means that customers are limited on the variety of components they can choose from. Currently, customers may design in a component that is very similar to that of another customer. If they both used the identical component, the purchasing could be simplified and inventory would be reduced. If many components are shared between products, surface mount setups could be reduced by using the same kit and setup for those products.

7. Conclusions

7.1 Summary and Lessons

Reducing cycle time is a useful method to improve all aspects of a factory. It drives out waste, highlights the importance of quality, and provides better customer service. A factory's cycle time must be looked at holistically. Improving the rate at which one aspect of the factory performs may have very little impact on the total factory cycle time. Instead, overall improvements such as WIP reduction and lot size reduction can provide great improvements in cycle time. The reduction of safety stocks and increase in the number of setups motivates all areas the factory to reduce setup time and variability. This has been observed in both the factory and is supported by the literature.

Much improvement can be obtained through continuous improvement. These efforts expose weaknesses in the current factory design. These weaknesses will limit improvement. As improvement slows, factory redesign may be necessary to reach the desired level of improvement. In CBA1, the factory redesign reduced sources of variability and queuing built into the original factory design. Once the redesign is fully implemented, continuous improvements must begin again. When the improvement efforts plateau, factory redesign should be considered again.

The data analysis combined with observations proved useful in understanding the contributors to the cycle time. Even though the analysis parsed the cycle time in many different ways, it did not directly point to these contributors. It only showed the impact each operation, line or workcenter had on cycle time. But comparing the data on a cycle time to the observed process yielded the understanding that reducing WIP levels and lot sizes would provide the most leverage in reducing the cycle time. This knowledge focused improvements not on the worst operations (those with the longest cycle time), but on the overriding factors that impact cycle time.

Reduction of WIP levels was achieved primarily through two methods: CONWIP implementation and standard lead time reduction. The CONWIP implemented in this factory measured WIP inventory by the minutes required to manufacture the material at the bottleneck. The CONWIP is extremely useful in a factory where it is difficult to visually understand the amount of work represented in the WIP. The CONWIP functions in conjunction with the MRP system. MRP provided the order of releases necessary to meet customer demand, while the CONWIP actually controls when a job may be released. If some of the jobs recommended for release by the MRP system cannot be released because the CONWIP is full, overtime must be worked or customer schedules modified.

Finally, the factory redesign team set as a goal the improvement of customer satisfaction: cost, quality and service. This broad focus greatly impacted the final design. Features to improve quality and cost were considered equally with features that improve cycle time. The team understood the impact quality improvements would have on both cycle time and cost. The large number of participants in the design process has created a shared vision of where CBA1 is heading. With this vision, the new factory design and future improvements will certainly be successful.

7.2 Results

The continuous improvement efforts at CBA1 resulted in a reduction of the manufacturing cycle time from a high of 8.7 days to the current 4.9 days. The associated WIP reduction is valued at over \$750,000. In addition, management of production has become easier and quality problems are more obvious.

A factory redesign team was formed in September of 1996 and implementation of the new design began in December of 1996. Currently, the final features of the new design are being implemented and continuous improvement efforts have begun. The new design reduced the factory floor space from 20,000 to 12,000 square feet. This floor space averted a need to expand CBA1, a savings valued at approximately \$1 million. In

addition, the number of surface mount lines has been reduced from 3 to 2, reducing the capital component of assembly cost. These improvements are summarized in Table 7-1.

Improvements	Values
Cycle Time Reduction	8.7 to 4.9 days
WIP Reduction	\$750,000
Factory Floor Space	20,000 to 12,000 sq. feet
Number of Queues	20 to 7
Cost Avoidance from Floor Space	est. \$1,000,000

Table 7-1: Summary of Improvements

7.3 Recommendations

7.3.1 Continuous Improvement

The process of continuous improvement should continue once the new factory design is implemented. The efforts outlined in Section 6.4 are a good starting point.

Benchmarking of competitors and surveys of customer needs are valuable tools to determine which improvements are most needed. Even when cycle time is reduced below one day, improvements in cost and quality will continue to improve customer satisfaction.

7.3.2 Cost Model

The cost model used in this factory has drivers for equipment setups, kitting, and orders. These drivers charge customers based on how many lots are produced, creating an incentive for larger lot sizes. These larger lot sizes create increase WIP and finished goods inventory, increasing the associated inventory management costs and delay in receiving quality data from customers, while reducing the factory flexibility. Instead, these setup, kitting and order costs should be amortized across all products, possibly based on cost or total demand volumes. Reducing or eliminating these per lot charges will

free up the factory to create lot sizes that are optimal for the entire factory instead of the current system which optimizes for each product. It will also provide an incentive for the factory to improve these areas since cost to perform these tasks would be higher than what is charged.

Additional charges can be created to provide incentives for customers to improve their products. Increasing the charges for higher cost, lower quality processes above their real costs will provide added incentive for customers to switch to more cost effective processes. Or savings can be given for using standard components.

Many of these cost model changes are just more accurate measures of the true costs. For example, the cost of purchasing all components for a product is based on the number of unique components on the board. Although using the same components as other products would reduce the purchasing costs, this is not included in the model. Looking to see if these components are shared with other products is not included. Setup and kitting costs currently drive lot sizes higher. But if inventory and quality costs were included, this would increase charges for larger lot sizes.

7.3.3 Measures

A few of the current measures conflict with cycle time improvement. While important, a push to increase utilization that only piles more inventory on the next workcenter does not increase the factory's output. Instead, higher level measures like factory output, inventory and manufacturing cycle time should be used at all workcenters. Operators should be given the freedom to move to the location where they can best impact these measures. This could mean that a kitting operator works occasionally in the test area. Only the factory's bottleneck operation should have a utilization as a measure. Again, all in the factory should understand this measure and should contribute to its improvement, even if it is not their direct responsibility.

7.3.4 Workcenter Optimization

The major focus of the latter half of the project was to redesign the factory, while less emphasis was given to examining the workcenters. As cycle time comes down, the processing time at the individual workcenters will dominate. A focus on each workcenter will certainly be rewarded with additional cycle time improvements.

7.3.5 Factory Redesign

The new factory design described in this thesis was developed when cycle time was greater than 5 days. As cycle time continues to improve, a better understanding of the problems will lead to better solutions. Also, the environment within which CBA1 is working is constantly changing. Product mix and complexity will change over time. The competitive environment will change. The factory may need to be redesigned again to incorporate this new understanding or changes in the environment.

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