

Implementation of Remote Monitoring System in Printed Circuit Board Assembly Equipment

by

Sandeep Sadashivappa

B.S., Mechanical Engineering
Ohio State University, 1996

Submitted to the Department of Mechanical Engineering
In Partial Fulfillment of the Requirements for the Degree of

Master of Science in Mechanical Engineering

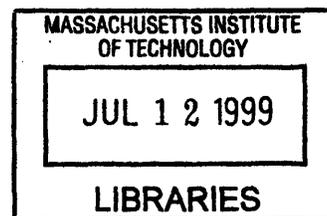
at the

Massachusetts Institute of Technology

September, 1998

© Massachusetts Institute of Technology, 1998.
All rights reserved.

ENG



Author
Department of Mechanical Engineering
August 15, 1998

Certified by
Duane S. Boning
Associate Professor of Electrical Engineering and Computer Science
Thesis Supervisor

Certified by
David E. Hardt
Professor of Mechanical Engineering
Thesis Supervisor

Accepted by
Ain A. Sonin
Chairman, Committee on Graduate Students, Mechanical Engineering

Implementation of Remote Monitoring System in Printed Circuit Board Assembly Equipment

by

Sandeep Sadashivappa

Submitted to the Department of Mechanical Engineering
on August 15, 1998 in partial fulfillment of the requirements for the degree of
Master of Science in Mechanical Engineering

Abstract

In capital intensive factories and manufacturing lines, the penalty for downtime for any individual piece of manufacturing equipment is very high, not only in lost production, but also in potentially undetected problems in in-process inventory. Early detection of problems, preferably before they become serious, and rapid response to repair or compensate are a high priority for all manufacturing facilities. Real time monitoring of the manufacturing equipment and process is now possible due to the increased amounts of instrumentation and networking capabilities provided by equipment vendors. However, the large amounts of data that manufacturing equipment can now provide can be overwhelming for data analysis, the networking infrastructure, and the data handling ability of the database. The objective of this project is to implement remote monitoring capability in a specific manufacturing facility to demonstrate how to determine which variables are of most importance, how to use that data, and how much benefit can be provided by the addition of the monitoring capability.

The printed circuit board assembly area of the North Penn Electronics Facility was selected as the target of this study. A system to monitor the component pick performance of the individual feeders on the surface mount pick and place machines was developed. This system was implemented into the plant using a subset of the features specified on the original design. The monitoring system has been tested, and results indicate that more complete statistical process control rules as specified in the original design are needed to fully address the component scrap and machine downtime issues.

Thesis Supervisor: Duane S. Boning

Title: Associate Professor of Electrical Engineering and Computer Science

Thesis Supervisor: David E. Hardt

Title: Professor of Mechanical Engineering

Table of Contents

List of Figures	4
List of Tables	5
Chapter 1: Introduction	6
1.1. Purpose	6
1.2 Literature Review	7
1.3 Thesis Outline	8
Chapter 2: The Surface Mount Assembly Process	9
2.1 Introduction to Surface Mount Technology	9
2.2 Overview of Assembly Process at North Penn	12
2.3 Pick and Place Machines	14
Chapter 3: Feeder Performance Monitoring System	16
3.1 Motivation	16
3.2 Implementation.....	19
Chapter 4: Analysis of Feeder Scrap Data	22
4.1 Data Collection.....	22
4.2 Data Integrity.....	23
4.3 Data Analysis and Evaluation	26
Chapter 5: Results of Feeder Monitoring System	30
5.1 Results	30
5.2 Future concerns	30
Chapter 6: Conclusions	34
6.1 Summary	34
6.2 Future Work	36
Bibliography	38
Appendix A: Sample calculations for Analysis of Variance	39
Appendix B: Summary of feeder performance by machines	42

List of Figures

Figure 2.1: Through hole components require holes through the printed circuit board for insertion of their leads while surface mount components are placed on the surface of the printed circuit board. (A) shows a typical through hole component while (B) shows a surface mounted component. Both are shown in side view..... 10

Figure 2.2: The assembling of a printed circuit board with surface mount components has three basic steps: solder paste is applied onto that blank boards, components are placed onto the boards, and the whole assembly is reflow soldered. 10

Figure 2.3: This figure shows how the three steps of assembling a printed circuit board with surface mount components are accomplished at the North Penn Electronics Facility. Note that a typical line contains three different types of pick and place machines in series. 11

Figure 3.1: This categorical breakdown of OEE at the North Penn Electronics Facility by week from March 1 – June 28, 1997, shows that improvements in to address efficiency will have the greatest impact on improving the OEE. 17

Figure 4.1: Example of potential application of feeder performance monitoring system. Miss-pick rate is plotted with the half hour time period it represents. Data represents one feeder from July 13 – July 22, 1998. 29

List of Tables

Table 3.1: New tables added to plant database to store data for the Feeder Performance Monitoring System.....	21
Table 4.1: Average component scrap rate for each GSM machine in lines 1-5 in CSMD area.....	26
Table 4.2: Pick performance by feeder location on GSM5.....	27

Chapter 1: Introduction

1.1. Purpose

In capital intensive factories and manufacturing lines, the penalty for downtime for any individual piece of manufacturing equipment is very high, not only in lost production, but also in potentially undetected problems in in-process inventory. Early detection of problems, preferably before they become serious, and rapid response to repair or compensate are a high priority for all manufacturing facilities. Real time monitoring of the manufacturing equipment and process is now possible due to the increased amounts of instrumentation and networking capabilities provided by equipment vendors. However, the large amounts of data that manufacturing equipment can now provide can be overwhelming for data analysis, the networking infrastructure, and the data handling ability of the database. The objective of this project is to implement remote monitoring capability in a specific manufacturing facility to demonstrate how to determine which variables are of most importance, how to use that data, and how much benefit can be provided by the addition of the monitoring capability.

The North Penn Electronics Facility in Lansdale, Pennsylvania was chosen as the target of the study because its process of assembling printed circuit boards lends itself well to remote monitoring and diagnostics: it is a high throughput, high precision process capable of gathering large quantities of data. The plant, formerly part of Ford Motor Company's Automotive Components Division (renamed Visteon), manufactures a variety of electrical components used in automobiles such as the electronic engine control modules (EEC), speed control amplifiers (SCA), mass air flow sensors (MAF), and anti-lock brake modules (ABS) among others. This study was primarily concerned with the EEC assembly process.

The objective of this project is to design and implement a system capable of monitoring the performance of the component feeders on one of the pick and place machines used in the EEC assembly process. The system must be designed to monitor the performance of every feeder on this machine, on every production line, and alert operators to potential faults using a set of statistical process control rules. Details regarding the pick and place machines and component feeders, as well as the motivation for choosing this aspect of the manufacturing process as the primary focus are explained in Section 2.3 and Section 3.1. The monitoring system is expected to have an immediate impact by reducing the component scrap rate and a long term impact of decreased machine downtime. The actual implementation and use of this system will be the responsibility of the plants Information Systems department and production engineers.

1.2 Literature Review

The components used on the EEC boards at North Penn are almost exclusively surface mount devices. Surface mount technology is a relatively new development tracing its origins to the 1960's. Surface mount technology (SMT) was considered vital for military and aerospace needs to satisfy the high component density and low weight requirements for critical applications. Now, SMT is becoming more widely used in many applications that require printed circuit board assemblies. Considerable work has been done in advancing the technology to mainstream usage. Works from Prasad [1], Lea [2], and Capillo [3] provide detailed information on the background of SMT as well as parameters to consider in its design, manufacturing, and assembly onto a printed circuit board (PCB). Further details of the assembly process that mounts the components onto the PCB are addressed by Kear [4].

Once an area of the assembly process is chosen as the target for the monitoring system, the available data must be analyzed in real time to detect any potential faults. Statistical data analysis techniques used in this thesis were drawn from Devor [5],

Montgomery [6], and Box [7]. More advanced fault detection techniques are discussed by De Kleer, Williams [8], Lin [9], Brown, and Hwang [10].

1.3 Thesis Outline

Because this project deals with the implementation of a monitoring system in a printed circuit board assembly plant, background on the assembly process will be presented first. Chapter 2 presents a background to surface mount technology and how it is used in North Penn. Some details regarding the specific process and types of machines used at North Penn relevant to the pick and place monitoring problem are given. Chapter 3 discusses the actual monitoring system developed in this project. It begins with a motivation for the project that explains the reasoning behind certain decisions regarding which aspect of the assembly process to focus the monitoring system. Chapter 3 also provides some details about the system hardware and software.

Before the monitoring system was developed, baseline data was collected and analyzed. This analysis was necessary not only to use in a before vs. after comparison, but also to ensure that some of the assumptions made along the way were valid. The analysis is also a means of discovering additional trends in the performance that can be utilized in the development of the monitoring system. Chapter 4 discusses what data was collected, why it was collected, and how it was used. During the course of this project, several concerns regarding the validity of the data stored in the plant database surfaced. These are also discussed in Chapter 4, along with a summary of machine performance with regard to component scrap rate.

Chapters 5 and 6 both pertain to the evaluation of the monitoring system after it was developed and implemented. Chapter 5 explains some of the shortcomings of the system in its current form and how these can be improved. Chapter 6 presents a summary of the thesis as well as potential areas of focus in future projects specifically at North Penn.

Chapter 2: The Surface Mount Assembly Process

2.1 Introduction to Surface Mount Technology

Currently, two methods of attaching electrical devices onto printed circuit boards are widely used. The conventional through hole method requires holes drilled into the board for the insertion of the leads of the electrical component. The leads are then soldered on the bottom side of the board. The more recent surface mount method places component leads onto tracks on the surface of the board and solders them in place. Figure 2.1 shows how an attached component appears with each method.

Surface mount technology is a relatively new method of attaching components onto a PCB. Surface mount devices are smaller and allow assemblies of lower cost, less area, less mass, and better vibrational control [1]. However, assembly equipment can be expensive, and because of the extensive use of automation and high speed, surface mount assemblies can result in high scrap rates. Several variations on how surface mount components can be used to assemble a PCB exist [2]. For example, a board may be single sided or double sided, it may use only surface mount devices (SMDs) or a combination of SMDs and through hole components. The board may combine SMDs and through hole components on one side or use only one type on a given side of the board. Each variation has its own preferred assembly process regarding which components must be placed first and which soldering method, reflow or wave soldering, is preferred.

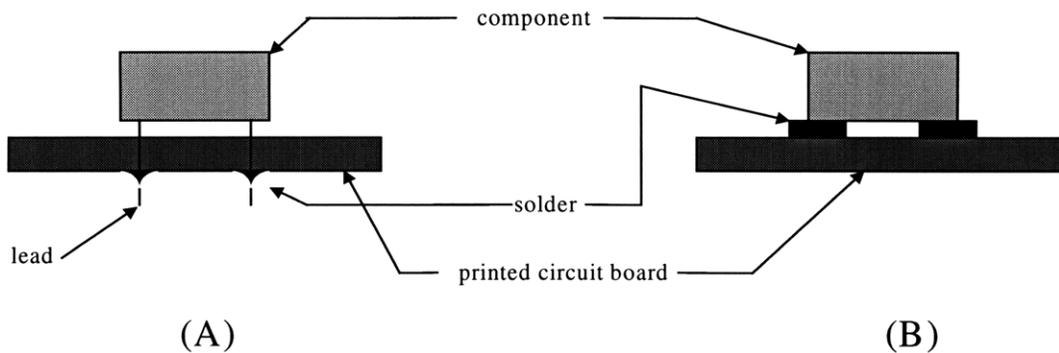


Figure 2.1

Through hole components require holes through the printed circuit board for insertion of their leads while surface mount components are placed on the surface of the printed circuit board. (A) shows a typical through hole component while (B) shows a surface mounted component. Both are shown in side view.

The electronic engine control modules assembled at North Penn are double sided and use SMDs almost exclusively. Figure 2.2 shows the general process used to assemble one side of a PCB of this nature. Section 2.2 describes how this process is used at the North Penn Central Surface Mount Device (CSMD) area where the EEC modules are assembled. Figure 2.3 provides an overview of a typical production line at North Penn.

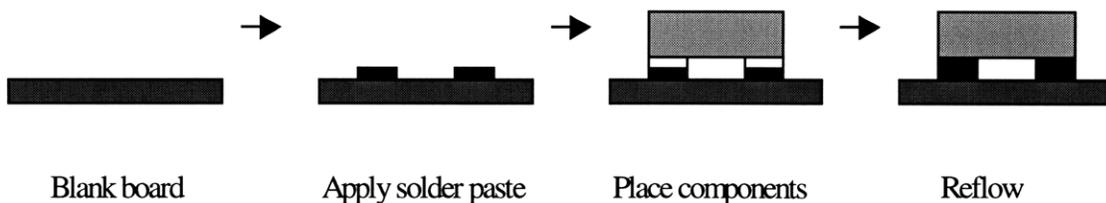
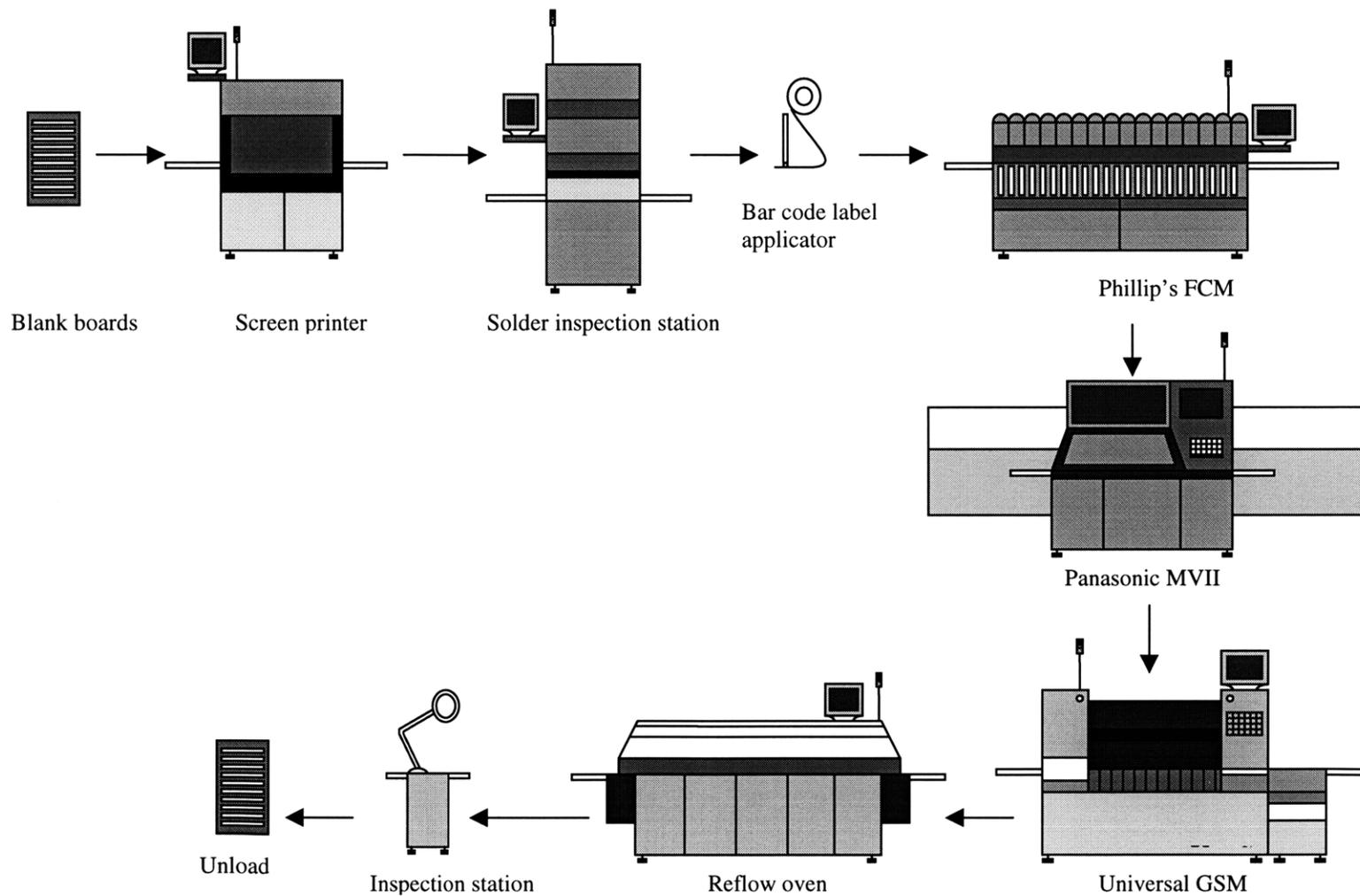


Figure 2.2

The assembling of a printed circuit board with surface mount components has three basic steps: solder paste is applied onto that blank boards, components are placed onto the boards, and the whole assembly is reflow soldered.

Figure 2.3

This figure shows how the three steps of assembling a printed circuit board with surface mount components are accomplished at the North Penn Electronics Facility. Note that a typical line contains three different types of pick and place machines in series.



2.2 Overview of Assembly Process at North Penn

The production process at North Penn's CSMD area begins with blank printed circuit boards which are stacked in automatic loaders at the beginning of each production line. The boards are loaded onto a screen printer where the solder paste is printed through a metal stencil using a rubber squeegee. Paste is applied to all the necessary pads in one parallel process lasting about 15 seconds. A typical EEC board assembled at North Penn may have several hundred pads for solder paste.

Following the screen printers is an inspection station that checks all boards for proper solder application. An inadequate amount of solder could result in an open electrical connection while excessive solder could cause an electrical short between adjacent pads when the solder is heated. The inspection utilizes a laser shadowing technique to perform a pass/fail test for location and volume of solder paste on every pad on the board in about 15 seconds. The boards that are rejected are wiped clean and reprinted. All boards that pass are labeled with a bar coded sticker that can be scanned at anytime in the manufacturing process or in service to determine when the board was assembled, which line it was assembled at, and which vendor and lot the components came from.

Once the boards are printed with solder paste and labeled, they are ready to be populated with components. This is the most crucial step requiring considerable accuracy and speed. North Penn uses three machines in series on each line. Each model of machine was selected to optimize the handling of certain types of components and so differ considerably in their operation and number of components placed. The types of machines used and their details are explained in the next section, but the basics are the same. The pick and place machines use a vacuum nozzle to pick a component from a supply and place it in the proper location on the printed circuit board. The components are packaged by the vendor in tape reels which are mounted onto feeders to supply the machines. The purpose of the feeder is to hold the tape reel, provide a location for the vacuum nozzle of the machine to pick up the component, and increment the reel to advance the next component into place. However, the feeders vary from being simple mechanical devices that

increment the tape reel through the use of a lever actuated by the part of the machine that contains the vacuum nozzle, to more complicated ones that are pneumatically powered and electronically controlled. A typical board may contain over 100 components.

After all the necessary components are placed onto the board, it proceeds through a reflow oven to form a secure mechanical and electrical bond at the solder points. The boards are then inspected manually before being stacked in magazines. Now the boards are either ready to have the bottom side populated or move on to the final assembly area.

In the final assembly area, each board undergoes a more thorough testing process to find any faults such as missing components or open/short contacts. Boards that are faulty are sent to a repair station where the mistake is corrected manually. Boards that are deemed satisfactory receive any necessary programming before being packaged in a thin silicone film for protection against the elements seen in service on an automobile, and encased in an aluminum housing for durability. The unit is shipped to the body and assembly plants ready for installment into the automobile.

Boards can be rejected in one of two stations: the manual inspection at the end of the reflow oven, or at the contact tests performed in the final assembly area. The operator at the manual inspection station can realistically check about 40% of the boards exiting the line. The inspector can also only hope to catch obvious errors such as a large missing component. The contact test in the final assembly area automatically tests each board using a bed of nails technique to check a predefined set of contacts. These tests can determine if there are any missing components or if there are any open or shorted lead contacts. When in the repair area, the bar code of the board is scanned and all information regarding which component is missing or which contacts are short/open is provided to the repair operator. This information can also be checked to find which line and which machine were responsible for the error, and when it occurred.

2.3 Pick and Place Machines

The function of the pick and place machines is the actual population of the printed circuit board with components. Because of the small sizes and the large numbers of the components that must be placed, these machines tend to be highly automated to maximize both speed and precision. Although the North Penn CSMD area uses machines from three different manufacturers, they all share a few basics of operation.

As a new board enters the machine, it is detected by optical proximity sensors. The board is positioned in a specific spot and the machine visually scans to locate several fiducials on the board. These fiducials are markings on the board used by the machine to determine the exact positioning of the board. Now each component is placed onto the board at a preprogrammed location relative to the fiducials. The placement process is entirely open loop with no feedback regarding the position a component was placed at.

Except for a few cases, the components are supplied in tape reels. The reel is mounted onto a feeder which is in turn mounted onto the machine in a particular slot. As the machine picks up one component, the feeder increments the reel in preparation for the next pick attempt. A vacuum nozzle is used to pick up the component and a brief burst of air through the same nozzle is used to shoot the component into location. Each time the machine picks up a component, the nozzle and the component pass through a visual scan. This scan determines the number of leads on the component, the shape of the component, and where exactly on that shape it has been picked up by the nozzle. This highly precise positioning information is used to place the component more accurately by correcting for any translational or rotational variance in picking component after component. At this vision check, the component may be rejected and a new component may be picked for several reasons. If the number of leads is incorrect (possibly due to bent or missing leads), if the component is missing, or if the position of the nozzle on the component is beyond the ability of the machine to correct for accurate placement, the machine simply discards the component and picks a new one. If there are several miss-picks in a row (the actual number defined during machine configuration), the machine will stop operation and notify the operator of a possible parts exhaust.

In each machine, a Reel Verification System (RVS) is used to prevent an incorrect component from being loaded into the wrong feeder slot. Anytime a feeder is mounted onto the machine, the operator must scan a bar code on his/her badge, another bar code on the component reel (identifying the type of component as well as vendor and lot data for future use), and the feeder location on the machine. Each machine location is only permitted to have one type of component in it, and so the machine can notify the operator if he/she is attempting to put the wrong component in the given slot.

Three types of pick and place machines were chosen to maximize efficiency and throughput. The Fast Component Mounter (FCM) made by Phillips specializes in the rapid placement of the small components such as resistors and capacitors. It consists of sixteen heads with one vacuum nozzle on each. Each head has five feeders to choose components from and operate on the board in series (sixteen boards can be in the machine at any given time). The General Surface Mount (GSM) made by Universal Instruments specializes in large, often fine pitched components, such as integrated circuit chips. It consists of one head with four vacuum nozzles picking components from about fifty feeders. The MVII machine made by Panasonic Factory Automation is a turret machine that places many “in between” components and is used for specialty runs because of its flexibility.

Chapter 3: Feeder Performance Monitoring System

3.1 Motivation

Total Quality Management (TQM) and Total Productive Maintenance (TPM) are two popular programs used by many industries today designed to improve the manufacturing process[11]. While TQM focuses on perfecting product quality, TPM attempts to perfect equipment productivity. The first step in TPM is to identify different metrics that can be used to quantify equipment usage and productivity. These metrics can then be combined to provide one value expressing the utilization of a given machine or a given production line. One such value is the Overall Equipment Efficiency (OEE).

The OEE presents a value, in percent, of total equipment utilization by measuring equipment availability, efficiency, and product quality.

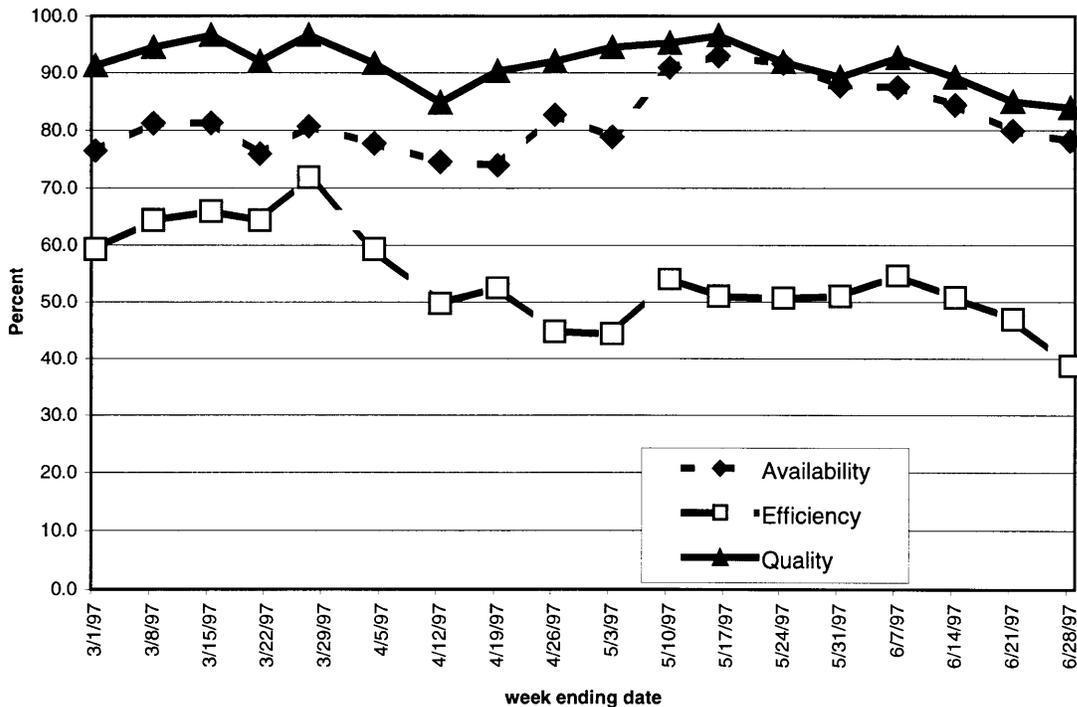
$$OEE (\%) = Availability (\%) \times Efficiency(\%) \times Quality (\%) \quad (3.1)$$

Equipment availability is the amount of time a given machine is scheduled for production as a percent of the total time. This value penalizes for scheduled maintenance or other expected off-production time. Equipment efficiency is measured as the quantity of product output as a percent of the maximum quantity of product that could be produced in the same amount of time. The maximum is calculated using an ideal cycle time or production rate for the given product. This value penalizes for situations that cause an increase in cycle time or cause the equipment to sit idle for any length of time. The product quality is a measure of the quantity of acceptable product produced as a percent of total production. This value closes the loop between equipment production rate and output quality by penalizing for any defects or poor process control.

Figure 3.1 shows the weekly values for each of the components of the OEE as measured at the North Penn CSMD area between the months of March through June, 1997. During this four month period, the overall OEE was 40%. Since the OEE is the product of three percent values, it can never be larger than its smallest component. At North Penn, the limiting factor, as seen in the graph, is equipment efficiency. Machine stoppages are quite common, usually due to feeder/component related problems at the pick and place machines. Low buffer spaces between these machines often causes these stoppages to propagate to other machines in the production line by starving downstream machines and blocking upstream machines. Most of these stoppages are not due to any significant failure that requires considerable downtime for maintenance, but usually many small stoppages that add up the lost production time measured in the equipment efficiency metric.

Figure 3.1

This categorical breakdown of OEE at the North Penn Electronics Facility by week from March 1 – June 28, 1997, shows that improvements in to address efficiency will have the greatest impact on improving the OEE.



Based on interviews of the plant engineers, it was determined that the single largest contributor to both machine downtime as well as component scrap was feeder performance. Faulty feeders could cause an abnormally high number of components to be scrapped yet go unnoticed by the operators. Faulty feeders can also cause machine stoppages due to tape jams or improper incrementing, and may increase the cycle time by forcing the machine to continuously re-pick any miss-picks. The only method of alerting the operator of poor feeder performance by the machine itself was if there were a certain number of consecutive miss-picks, usually from a parts exhaust, that caused the machine to stop. This method, however, is inadequate in detecting most of the faults that could cause poor feeder performance.

Routine maintenance on all feeders would help address some of these faults, but is not feasible for two reasons: the high demand for feeders and the inability to track performance after maintenance. Because the number of feeders available relative to the demand is fairly low, production might be sacrificed if large numbers of feeders have to be taken out of the loop for regular maintenance. In addition, the only way to track performance after maintenance is by manual records that show how often the feeder was serviced, not an actual pick performance record. A system to monitor the performance of each feeder could help operators catch faulty feeders before large numbers of components are scrapped.

North Penn Electronics Facility's CSMD area is undergoing considerable change during the term of this project. The number of production lines and the type of machines used is changing as well. On the five original production lines, one GSM is used per line. On the eight new lines being brought into production, two GSMs are being used per line. Because of this commitment to using the GSM, and because the GSM deals with larger, considerably more expensive components than the other placement machines, it was decided to focus on the GSM machines for this project. Specifically, the GSM on line 5 would be the testbed, although the underlying software would be developed to handle all GSMs simultaneously. The data used in this project is collected from the GSM machines on lines 1 through 5 only.

The GSM machine is capable of providing data regarding the number of pick attempts and the number of successful placements for each feeder location. The difference between the two numbers represent miss-picks, some of which would be a result of a missing component (such as if there is a parts exhaust), the rest representing scrapped components. This data is uploaded to the plant database and used to determine an aggregate number of each type of component scrapped, usually over a weeks worth of time. This allows a holistic picture of which components are being scrapped most, but prior to this project, this data was not being used to determine a scrap rate per component or feeder, or to reduce the number of components being scrapped.

3.2 Implementation

Although the machine provides pick performance data by feeder location, this does not necessarily represent the performance of one feeder. Typically, when there is a parts exhaust situation, the appropriate feeder is dismantled from the machine, a new reel is fixed onto the feeder, the new reel is scanned into the RVS system, and the feeder is remounted onto the machine. However, operators will often have spare feeders waiting off line with a fresh reel of components. When there is a parts exhaust, the original feeder is dismantled, and the new reel and feeder is used in that feeder location. This is done to speed up the reel changing process and is particularly common when one component is used excessively or if there are only a few feeders being used for a particular type of board. If new feeders are mounted onto a given feeder slot on the machine, the data stored by the machine is not indicative of the pick performance of any one feeder. If the feeders are interchanged frequently, there will be considerable variance in the performance data stored for one feeder location in the plant database. This indeed is what is observed for the GSM machines.

The initial plan for the feeder monitoring system was to individually label each feeder with its own unique bar code which would be scanned along with the usual scanning process required by the RVS system whenever a new feeder is mounted onto the machine.

This information could be added to the plant database along with the performance data already being collected by the machine by feeder location. The information could then be cross-referenced to provide performance data by feeder even if the feeder is used in multiple lines. This performance data could be monitored in real time and could alert the operator of poor performance that could indicate a fault requiring maintenance. The system could also locate the feeder and monitor its performance after service to determine the effect of the maintenance. An X terminal would be placed on each line to display the performance of the feeders currently being used on that line's machines.

North Penn's Information Systems (IS) department stated that labeling each feeder with a bar code and incorporating that information into the RVS and plant database would require considerable time and resources. Because of the difficulties involved in the installing and preparing of the eight new lines in the CSMD area, the CSMD personnel were not willing to make the labeling of the feeders a high priority for the IS department. Therefore, it was decided to develop the monitoring system without labeling each feeder. Instead the pick performance would be monitored by feeder location on the machine. Since the feeders can be interchanged for each feeder slot on the machine, performance data by feeder location does not directly correlate to the long-term performance of a given feeder. It does however represent the feeders performance over a short term (the time period accurately represented depends on the frequency of feeder exchange used by the operators). This data is already being collected and stored in the plant database. The pick performance data can then be used to determine faults using various fault detection criteria.

The Universal GSM communicates pick and place data for each feeder location to the plant host every half-hour through a GEM-SECS II interface. This information is translated through a custom C++ interface and a custom Perl translator/stuffer before finding its way to an Oracle database. This data is compared to a set of process control rules to determine if the pick yield is acceptable. Any instance that performance for a given feeder location fails one of these rules, a red alert window displays the location and pick data on an X terminal located near the GSM on line 5. To address the alerts that arise, the operator scans his/her badge as a user ID, selects the incident that is being addressed,

and scans the type of resolution action taken. Currently, there are seven possible resolutions that can be selected:

1. Feeder adjustment
2. New feeder installed
3. Equipment adjustment
4. Reel/vendor problem
5. Maintenance/Troubleshoot
6. No problem found
7. Insufficient picks

The feeder performance monitoring system adds four new tables to the plant database. The names and function of each are detailed in Table 3.1.

Table 3.1

**New tables added to plant database
to store data for the Feeder performance Monitoring System**

Table Name	Function
NPCIM_FEEDER_EVENTS	stores the events that fail to meet the acceptability criterion.
NPCIM_FEEDERS_STATION_CFG	stores the configuration for the thresholds being used by each machine.
NPCIM_RESOLUTION_CFG	stores the configuration for the valid resolutions that can be selected.
NPCIM_USER_ID	stores the configuration for the valid users.

Chapter 4: Analysis of Feeder Scrap Data

4.1 Data Collection

As mentioned in the previous chapter, the Universal GSM communicates component pick and place data for each feeder location to the plant host every half hour through a GEM-SECS II interface. The difference between these two numbers, the miss-picks, are a result of components being rejected by the vision system of the machine. This can occur for three main reasons: there is no component on the nozzle, the placement of the nozzle on the component is such that the machine cannot compensate for a proper placement, or the component has damaged or missing leads. Although the machine has the capability to detect damaged or missing leads, this option usually not enabled on the GSMs at North Penn. In this paper, miss-picks and component scrap are used interchangeably, although not every miss-pick will result in a scrapped component. However, it is impossible to determine which miss-picks are really scrapped components and which are missing components due to parts exhaust or vacancies in the reel. Therefore, a worst case scenario is assumed at North Penn where all miss-picks represent scrapped components.

Except in the case of a parts exhaust or vacancy in the reel supply of components, all miss-picks are a result of some poor performance in the system. Some possible sources could be poor feeder performance, improper vacuum in the nozzle, error in the vision system, or a faulty component. However, based on the experiences of the plant engineers, it was assumed that poor feeder performance was responsible for the vast majority of miss-picks. If this is a valid assumption, the miss-pick rate should vary considerably from feeder to feeder within each machine. If however, the variance in miss-pick rate within a machine is low, while the variance in miss-pick rate between machines is high, then the miss-picks could be attributed to machine to machine variations such as nozzle performance. This

study reinforces the assumption that the miss-pick rate is primarily a function of feeder performance by analyzing the variance in the miss-pick rate within and between machines (see Section 4.3 for details). Once it is established that component pick performance is a good indicator of feeder performance, this data can be used in the feeder monitoring system.

4.2 Data Integrity

Several issues concerning the validity of the data stored in the plant database have surfaced during this project. All the problems trace their roots to the communication between the GSM machine and the plant host. Each GSM machine has a local database called the Management Information System (MIS) that stores process data including component pick performance numbers. This information is stored by product number, with all variables being reset whenever there is a product changeover. Ideally, the machine would send a message to the plant host whenever the variables were being reset along with all values for those variables since the last reset time. This way the machine would know which variables are being used (usually, only four to eight feeders out of the fifty or so available are used for any given product) and the values for all variables would match exactly. Since the communication with the machine is built on the SECS-II protocol, machine initiated transfers should be possible. However, the GSM does not have this capability.

Instead, the plant host queries the machine every half hour for values of all variables. Then, logic built into the system tries to determine when variables are reset, which variables were updated by the machine, and reports only those variables currently being used to the plant host. This is done to reduce the database size since there are often many unused variables. The result is a locally stored database that maintains data by output product (a product run can last anywhere from a few minutes to several hours), and a plant database that collects and stores data by the half hour. The discrepancy in how the variables are reset has caused several errors described in the following paragraphs. Since

the actual numbers in each database will be different, it is difficult to check the information in one database with that in the other to confirm validity.

The first problem that became evident was due to a misunderstanding about when the pick performance data was being reset. It was believed that the data from the machine was being reset each time it was queried for by the plant host. Since the host queried the machine for data every half hour, the underlying software assumed that any data received was for the previous half hour only. The data was therefore summed with previous time periods and a cumulative value for each shift was stored in the plant database. However, the machine was not resetting its values when queried by the plant host – it was already providing cumulative data. The end result was that variable values kept snowballing over a shift's worth of time and the values recorded in the database were often an order of magnitude higher than what they should have been. This error had gone unnoticed for over a year before this project drew attention to it in the summer of 1997. The software was corrected as of January, 1998.

The discrepancy in how the variables are reset also leads to the possibility that some data can be lost. For example, the plant host might query the machine at 12 noon and again at 12:30 p.m. However, if there is a product changeover at 12:20 p.m., the variables are reset at the machine and only the final ten minutes worth of data is reported to the host. The host's logic can determine that there was a changeover and that the values were reset, thereby resetting its own values. But it is not able to distinguish when in the last thirty minutes the reset occurred, and the data until the reset (in this example, the first twenty minutes worth of data) is lost.

When examining the pick performance data on the plant database, the most obvious anomaly is the existence of "negative" miss-picks. These negative miss-picks occur as often as five to ten percent of the data points recorded. Although physically impossible, the recording of these negative numbers is also a result of the timing of the host's queries. If the timing is just right, the host may query the machine during the few seconds between when a component is picked from its feeder and when it is placed on the board. If only one

component is caught in this “in-between” state, the first half hour’s worth of data will report one extra miss-pick since there was one extra component picked but not placed. However, this component could still be placed in the following time period. Now assuming that the machine in reality has no miss-picks, the next time period’s worth of data would report one extra component placed that was not picked. Since the column for component scrap (miss-picks) is calculated as the difference between components placed from the number of components picked, this scenario would result in a -1 scrap for the second half hour. Since the machine has four nozzles, it is capable of holding four components in this “in-between” state, and the maximum number of negative miss-picks that could occur in any time period is four. This in fact is what is observed, with most negative miss-picks being -1 and almost always preceded by a miss-pick value of $+1$. Not only can this be confusing for someone looking at this data for the first time, but this effect must be taken into consideration when developing control rules for the feeder performance monitoring system. Although this is not important when looking at aggregate totals, it can be misinterpreted when treating each time period’s worth of data independently, as the monitoring system does. When a miss-pick is reported, the miss-pick value for the next time period must be considered to determine if it is indeed a miss-pick or just part of the positive/negative combination.

On very rare occasions, other impossible scenarios will be recorded on the plant’s database. For example, negative miss-picks in the hundreds, positive miss-picks in the hundreds, or negative values for the number of components picked occasionally appear in the database. The reasons for these errors are unknown and are simply discarded in the analysis done in this paper. It is expected that there are loopholes in the host’s software logic that can result in odd scenarios. These problems, as well as all the ones described in this section, could be corrected if the GSM machine was capable of initiating the communication and transfer of information with the plant host. These issues were brought to the attention of Universal Instruments, and machine initiated communication capability is expected to be offered on future GSM models.

4.3 Data Analysis and Evaluation

Component pick performance data was collected over two time periods to determine a baseline performance for each machine. The first set of data is from February 23 to April 8, 1998, while the next set is from April 1 to June 30, 1998. As mentioned previously, the data is collected for each feeder every half hour. The number of times a certain feeder is used and the number of components picked from a certain feeder location varies greatly from one feeder to the next. Using a relatively large time frame of data helps to neutralize this variation in feeder usage.

Table 4.1 summarizes the mean component miss-pick rate for each machine over the two selected time periods. It should be noted that three of the machines, GSM2, GSM4, and GSM5, have very similar performance from one time period to the next. An analysis of variance was done to determine the statistical significance in the variation between machines (see Appendix A). Using the second set of data, the variation in performance between machines was found to be significant to a 66 % level of confidence. This is generally not a high enough level to nullify the hypothesis that there is no significant variation between each machine responsible for the different mean miss-pick rate [6].

Table 4.1

Average component scrap rate for each GSM machine in lines 1-5 in CSMD area

Machine	Feb. 23 – April 8, 1998		April 1 – June 30, 1998	
	Mean (%)	Std. Dev. (%)	Mean (%)	Std. Dev. (%)
GSM1	0.65	0.350	0.44	0.239
GSM2	0.45	0.261	0.43	0.185
GSM3	0.47	0.211	0.64	0.662
GSM4	0.55	0.400	0.58	0.373
GSM5	0.44	0.293	0.49	0.364

The mean pick performance of each machine is a combination of the performance of its many feeders. Appendix B shows the actual performance numbers for individual feeders in each machine. Because the sample size varies considerably for each feeder (some feeders performing two orders of magnitude more picks than others), only the feeders that were used the most were used in determining the variance within each machine. Table 4.2 shows an example of the performance by feeder for the GSM5 machine using the seventeen most active feeders.

Table 4.2

Pick performance by feeder location on GSM5

Feeder	Scrap rate from Feb. 23 – April 8, 1998 (%)	Scrap rate from April 1 – June 30, 1998 (%)	Absolute difference between scrap rates
F0001	0.24	0.24	0
F0003	0.43	0.71	0.28
F0005	0.46	0.67	0.21
F0008	0.36	0.54	0.18
F0021	0.49	0.47	0.02
F0023	0.43	0.46	0.03
F0030	0.18	0.23	0.05
F0032	0.34	0.39	0.05
F0037	1.29	1.22	0.07
F0041	0.20	0.21	0.01
F0043	0.66	0.20	0.46
F0045	0.22	0.24	0.02
F0047	0.28	0.22	0.06
F0051	0.56	0.24	0.32
F0107	1.05	1.27	0.21
F0110	0.66	1.12	0.46
F0130	0.66	0.71	0.04
Total	0.44	0.49	0.05

Of the seventeen feeders shown, ten have very similar behavior between the two time periods, differing by 0.07 % or less. The large range of possible usage of each feeder makes it difficult to calculate a variance within a feeder. When performing well, the miss-pick rate is 0 %. When performing poorly, the miss-pick rate might be 10%. When calculating the variance, this one large value will result in the overall variance within a feeder to blow up to unreasonable values. However, since about half of the feeders seem to perform very similarly over the two large time frames, it is assumed that the variance within one feeder is low. Meanwhile, the variance between feeders in one machine is quite high. For example, from Table 4.2, it can be seen that feeder F0041 consistently has a low miss-pick rate around 0.2%. The feeder immediately adjacent to it, feeder F0037, has a miss-pick rate that is consistently around 1.2% -- six times worse.

Since the variation in pick performance between feeders within one machine is high, but the variation between machines is relatively insignificant, the assumption stated earlier that the component pick performance is primarily a function of the feeders is supported. If the source of the variation was something common to all feeders such as the vacuum nozzle or vision system, the variation in pick performance within one machine (between feeders) would be low, while the variation in performance between the five machines would be high. The high variance in pick performance between feeders seems to indicate that improvements can be made at the feeder level to improve overall component scrap rates. Monitoring the feeder performance should keep tighter control over the pick process allowing each of the feeders to perform as well as the best feeders do now.

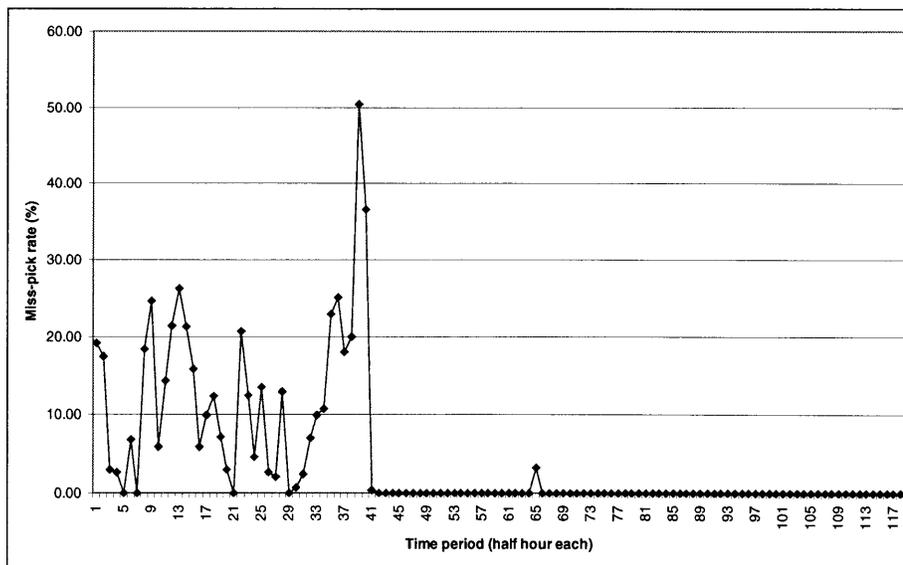
The general assumption is that each feeder has a certain characteristic behavior that can be represented by a binomial distribution defined by the mean and variance of the miss-pick rate [6]. The mean and variance should not be time dependant, and any variation in the feeder's miss-pick rate over time is indicative of a change in its fundamental performance. By monitoring the miss-pick rate over time, these changes can be detected and acted on before performance degrades. Although each feeder may have its own characteristic behavior, similar feeders should perform similarly. Using the miss-pick rate

to determine the mean and variance of each feeder allows for the determination of what type of performance is ideal, acceptable, and unacceptable for each type of feeder. Real time monitoring then helps find the feeders that are performing below an acceptable standard.

Time dependant variation in miss-pick rate can be seen qualitatively in the component pick data. Figure 4.1 shows an example of the pick performance of one specific feeder from July 13 to July 22, 1998. In this graph, the miss-pick rate is plotted as a percentage with the half hour time period it represents. There is an obvious difference in performance between the first 40 time periods and the last 80 time periods. The reason for the change is not known, but it is likely due to a change in feeders in the given location. A monitoring system using statistical process control rules (specific rules applicable to this system are explained in Chapter 5) will be able to determine that there is a potential problem with the feeder being used and notify the operator within five time periods instead of 40. As a result, the many components that were scrapped in the remaining 35 time periods could be saved.

Figure 4.1

Example of potential application of feeder performance monitoring system. Miss-pick rate is plotted with the half hour time period it represents. Data represents one feeder from July 13 – July 22, 1998.



Chapter 5: Results of Feeder Monitoring System

5.1 Results

At the time of this report, the feeder performance monitoring system has been in operation on one of the GSM machines for three weeks. Analysis of the component pick performance data over those three weeks show no significant improvement over the baseline performance presented in Chapter 4. This can be explained by three shortcomings of the system in its present state, which are explained in the following section.

5.2 Future concerns

The primary concern regarding the use of this system is how to capture faults without too many false alarms. To do this, the failure criterion must be robust. When the feeder performance monitoring system was developed by the plant's Information Systems department, the failure criterion was made very simple. A single, configurable threshold of the percent miss-picks was used. When the percent miss-picks for any given time period surpasses this threshold, the operators are notified. The IS department was unwilling to implement a more sophisticated set of process control rules until the system was used for some time.

This current criterion of a single threshold of acceptable yield is too simplistic for long term usage. It will be necessary to incorporate a set of statistical process control rules that will signify a fault. For example, one of the main reasons for an alert occurs when there are very few picks in a given time period. If only twenty components are picked in one time period and one is scrapped, the resulting miss-pick rate is 5% -- high enough to

trigger an alert. Yet one miss-pick out of twenty may not be statistically significant. However, if this same high miss-pick rate occurs three or four time periods in a row, it is worth looking into.

As mentioned in the previous chapter, it is assumed that each feeder has a certain characteristic behavior that can be represented by a binomial distribution. Any time dependant changes in this behavior, or unacceptable variation between similar feeders can be detected using simple statistical process control rules on the incoming stream of pick performance data. A closer examination of historical data can be used to determine control limits for a binomially distributed process [6]. General rules that should be used with this system include [5,6]:

Rule 1: Extreme points

Operators should be notified every time that the miss-pick rate for a feeder is higher than 5% for a given time period with more than one component miss-picked. Although the overall mean miss-pick rate is below 1% for each of the GSM machines, the variance seen from one time period to the next is quite high. For this reason, a fairly high extreme limit is chosen.

Rule 2: Linear trend

A feeder alert should be signaled when the miss-pick rate continuously increases for five consecutive time periods. This could indicate a mean drift in that feeder's performance.

Rule 3: Three out of five points

A feeder alert should be signaled when the miss-pick rate for any three out of five consecutive time periods is above 2%. While a miss-pick rate of 2% occurs occasionally, several occurrences in rapid succession is usually indicative of a mean shift followed by a long period of poor performance.

Rule 4: Running average

Operators should be notified when the average miss-pick rate over the last four consecutive time periods is higher than 2%. This rule attempts to detect a mean shift that may not have triggered one of the other rules.

As the system is used more, additional criteria could be developed. In addition, the actual values used to trigger the tests in the above rules can be refined. Certain values can be used for certain types of feeders to minimize undesired alerts while maintaining tight process control. These criteria, and any others that are found to be effective, should be incorporated into the software of this monitoring system.

The second concern regarding the application of the feeder performance monitoring system is how to determine what the appropriate resolution is to an alert. At times, a simple adjustment of the feeder in its slot will take care of the problem, while other times, it may be necessary to remove the feeder from production for maintenance. Sometimes an alert will demand immediate attention, and other times, it may be more prudent to ignore the alert so as not to sacrifice production time. These issues will be better understood with experience. As the system is used more, the operators will become more comfortable with it and will be able to determine what is most appropriate for the given situation.

During the initial three weeks of use, no real resolutions were taken on any alerts that surfaced. The majority of alerts were due to one miss-pick out of a small number of pick attempts, and the only resolution is to dismiss the alert because of too few miss-picks to be significant. As a means of introducing the operators to the system, they were instructed to only select the alerts with one miss-pick and mark it as a dismissal due to too few pick attempts. Any alerts with multiple miss-picks on any given time period were simply ignored so that no corrective action is taken in this important case. Although this system is now in place and the operators are looking at it, there is no real difference between the process now compared to before the system was implemented. Until real resolutions are enforced, the system is useless.

The third concern is over the inability to track the feeders. If the actual mechanical operation of the feeders is the root of the problem, monitoring performance by feeder location on each machine is taking an extreme, and perhaps inappropriate, shortcut. To truly monitor feeder performance, it is necessary to label each feeder with a bar code and incorporate this information in the plant database. Until this is done, the benefits of this system will never be fully realized. Figure 4.1 in the previous chapter provides one example of the shortcoming of this system without the ability to monitor the feeders themselves. Although there is an obvious change around time period 40, it is impossible to know what caused this change. It is most likely due to a change in feeders in the given location. It is possible that the feeder used for the first 40 time periods is faulty and was replaced with a better one. However, if this assumption is true, it is impossible to determine what happened to this faulty feeder after the change. Perhaps the fault was never detected and this feeder is now being used in a different location, perhaps even a different machine. If the fault was detected and the feeder was serviced, it is still impossible to tell how the feeder will perform after the maintenance. It may be a feeder that is permanently damaged that should be taken out of production, or it may work perfectly after maintenance. Without the ability to label and track each feeder, it is impossible to tell.

Chapter 6: Conclusions

6.1 Summary

As modern factories become more automated and processes become increasingly high speed, monitoring systems for fault detection and process control are logical steps in ensuring high quality yield. What parameters to monitor, how to monitor them, what type of fault detection techniques to use, and what resolutions should be taken are each issues that must be addressed on a case by case basis. The objective of this project was to design and implement a monitoring system to improve the component scrap rate and machine utilization in a printed circuit board assembly plant.

Based on machine downtime data and interviews with the plant engineers, it was felt that the greatest potential for a monitoring system was in the component feeders on the pick and place machines. The pick performance varies considerably between feeders and existing methods did not allow for the detection and service of faulty feeders. A feeder performance monitoring system would help control the pick and place process reducing the number of components discarded due to miss-picks, and reducing the amount of feeder related machine downtime.

A system capable of monitoring component pick performance in real time by feeder location was developed for the North Penn CSMD area. Unfortunately, the system was developed at the same time that the CSMD area was undergoing considerable change by introducing eight new production lines. The considerable cost, manpower, and product output represented by these new lines demanded the highest priority of the personnel in both the CSMD area as well as the Information Systems department. As a result, the feeder performance monitoring system was slow to be implemented, was not deployed in as

powerful or robust a form as it could, and is still slow to be accepted. At the time of this report, the system had only been active for three weeks. However, the monitoring system can provide no benefit in its current state because of inadequate fault detection criteria and the lack of any real corrective action to concerns signaled by the system. More complete implementation of the monitoring system design described in this thesis – particularly in the adoption of the statistical process control rules – is needed to achieve the potential benefits of the system.

The cost of scrapped components was a concern with the five original production lines. With the addition of eight new lines in the CSMD area, the cost of scrapped components will become a very high priority. It is felt that the feeder performance monitoring system does have the potential to reduce component scrap and machine downtime. However, certain changes, as described in Section 5.2, must be incorporated into the system. Once the new lines are established, perhaps more time and manpower can be devoted to the monitoring system.

In addition to providing a system that can be used to monitor and reduce component scrap throughout the CSMD lines, this project also helps focus the plant on the value of process data. Although vast amounts of data are collected in the plant regarding process parameters, time management, and product information, very little is actually used to improve the manufacturing process. Often the databases are obscure or poorly labeled, or daily production concerns leave little time for proper data analysis. Many times the production engineers do not know what data is being collected that may be relevant to them or how to access it. This lack of communication between the production engineers and the Information Systems department is the cause of both the incorrect data regarding component scrap for the GSM to go unnoticed for over a year (see Section 4.2), and the slow progress of this feeder monitoring project. Because so little data is actually used by the production engineers, the IS department is reluctant to spend the time and effort to develop new products that may also be unused. The data, however, can be very valuable if it is collected and analyzed in a systematic way. If this feeder performance monitoring

system is improved and used successfully, future efforts at using the available data to improve the production process will be treated more enthusiastically.

6.2 Future Work

In the field of printed circuit board assembly using surface mount devices, there are many critical applications that can benefit from a monitoring and fault detection system. In the actual pick and place process, monitoring feeder performance is the best way to maintain a low component scrap rate and reduce machine stoppages. Since the inception of this project, similar efforts to develop a feeder monitoring system have been undertaken by several of the companies that manufacture the pick and place machines used at North Penn. Both Panasonic and Universal Instruments are developing such systems, each in response to customers concerned with maintaining tight control of the feeders. As mentioned in the previous chapter, modifications must be made in both the actual capabilities of the system as well as its implementation. If performance alerts are ignored, or if the failure criterion currently used is not improved, the true value of this system will never be realized.

The feeder performance monitoring system was chosen as a means of demonstrating the value of a monitoring system in a production facility. In a facility as data rich and automated as North Penn Electronics Facility, there are many other potential applications of data analysis or remote monitoring. One possible application could be in incorporating the repair loop data into a model of the production line. Currently, any errors such as an incorrect or missing component remain undetected until the entire board is assembled and soldered. This has several drawbacks: the problem is not detected until considerable value has been added to an already defective board, the repair process becomes more expensive as the fault detection point is moved closer to the end product, and the delay in the fault detection could result in hundreds of faulty boards being produced before the problem is found and solved. Since the repair loop data includes information such as which line/machine the board was assembled at, the specific time, and component vendor and lot information, a model to predict assembly faults by monitoring machine process parameters could be developed.

Each of the machines currently has the ability to not only provide performance data, but also time management data, such as the time spent waiting for a board or time spent waiting for operator input. One of the most frequent causes of undesired machine stoppages is due to a failure at one machine causing upstream machines to be blocked or downstream machines to be starved. Investigating the time management data on each machine could provide a more complete picture of how the line performs as a series rather than each machine individually. Although this data might not be useful in real time, it could provide considerable insight when introducing new lines, as was done at North Penn during the last year.

Other data rich processes that could be used to develop fault detection techniques include the inspection station responsible for measuring the area and volume of solder that was screen printed onto each board. This machine generates vast amounts of data but its output is a go/no-go decision. Currently, this data is not stored or even observed. This data does, however, present the potential to develop a model of the screen printing process that could be used to ensure more consistent application of solder paste onto the boards. A good model could eliminate the need for an inspection station by ensuring proper solder application through tight process control.

Finally, there is the possibility of networking the data collection and fault detection techniques across multiple facilities. For example, Visteon has several electronics plants that use the Universal GSM. Monitoring process parameters across one machine and providing real time diagnostic capability based on performance across all machines in several locations would be a giant leap forward in process control.

Bibliography

- [1] Prasad, Ray P. Surface Mount Technology: Principles and Practices. Second Edition. Chapman & Hall. New York, New York, 1997
- [2] Lea, C. A Scientific Guide to Surface Mount Technology Electrochemical Publications Limited. Ayr, Scotland, 1988
- [3] Capillo, Carmen Surface Mount Technology: Materials, Processes, and Equipment. McGraw Hill, Inc., New York, New York. 1990
- [4] Kear, Fred W. Printed Circuit Assembly Manufacturing. Marcel Dekker, Inc., New York, New York. 1987
- [5] Devor, Richard E., Chang, Tsong-how, Sutherland, John W. Statistical Quality Design and Control: Contemporary Concepts and Methods. Macmillan Publishing Company. New York, New York, 1992
- [6] Montgomery, Douglas C. Introduction to Statistical Quality Control Second Edition. John Wiley & Sons. New York, New York, 1991
- [7] Box, George E.P., Hunter, William G., Hunter, J. Stuart Statistics for Experimenters: An Introduction to Design, Data Analysis, and Model Building. John Wiley & Sons. New York, New York, 1978
- [8] De Kleer, Johan and Williams, Brian C. "Diagnosing Multiple Faults" *Artificial Intelligence*. Vol. 32 (1987) pp. 97 – 130.
- [9] Lin, Ching-Fang Advanced Control Systems Design. PTR Prentice Hall, Inc. Englewood Cliffs, New Jersey, 1994
- [10] Brown, Robert Grover and Hwang, Patrick Y.C. Introduction to Random Signals and Applied Kalman Filtering Third Edition. John Wiley & Sons, New York, New York. 1997
- [11] Leachman, Robert C. "Closed-Loop Measurement of Equipment Efficiency and Equipment Capacity" *IEEE Transactions on Semiconductor Manufacturing*, Vol. 10, No. 1, February 1997.

Appendix A

Sample calculations for Analysis of Variance: Variation across machine

An analysis of variance is done to determine the significance of the differences in mean scrap rate between machines [5,6]. This is done by comparing the variance between machines to the variance within each machine. If the variance between machines is significant compared to the variance within the machines, then the assumption that there are true differences between machines is supported.

Within machine analysis

GSM1

Data pt.	Feeder	Scrap rate (%)	Residual (from unweighted mean)	Residual squared
1	F0001	0.23	-0.29	0.082
2	F0008	0.52	0.00	0.000
3	F0037	0.17	-0.34	0.119
4	F0039	0.24	-0.28	0.078
5	F0044	0.32	-0.20	0.040
6	F0101	0.32	-0.20	0.040
7	F0103	0.28	-0.24	0.058
8	F0105	0.59	0.07	0.005
9	F0108	0.81	0.29	0.087
10	F0111	0.36	-0.16	0.025
11	F0114	0.57	0.05	0.002
12	F0123	0.42	-0.10	0.010
13	F0125	0.67	0.15	0.024
14	F0128	0.60	0.08	0.007
15	F0131	0.91	0.39	0.155
16	F0134	0.94	0.42	0.177
17	F0140	0.90	0.38	0.146
18	F0143	0.45	-0.07	0.005
19	F0146	0.44	-0.08	0.007
20	F0166	0.64	0.12	0.013
	Total	0.52	0.00	1.082

Total number of points (n): 20
 Degrees of freedom (dof = n-1): 19
 Weighted avg. scrap rate: 0.44 %
 Unweighted avg. scrap rate: 0.52 %
 Sum of residuals squared (SS): 1.082
 Variance (SS/dof): 0.057

Similarly, the sum of residuals squared and variance is calculated for each of the five GSM machines.

GSM2:

Data points: 42
 Sum of residuals squared: 1.394
 Variance: 0.034

GSM3:

Data points: 11
 Sum of residuals squared: 4.38
 Variance: 0.438

GSM4:

Data points: 15
 Sum of residuals squared: 1.946
 Variance: 0.139

GSM5:

Data points: 17
 Sum of residuals squared: 2.128
 Variance: 0.133

Total within machine sum of squares: 10.930

Total within machine variance (SS_{total} / dof_{total}): 0.109

Between machine analysis

Machine	Data pts.	Unweighted avg. scrap	Residual (from grand mean)	Residual squared	Residual squared x number of data pts.
GSM1	20	0.52	-0.018	0.000	0.006
GSM2	42	0.44	-0.098	0.010	0.403
GSM3	11	0.58	0.042	0.002	0.019
GSM4	15	0.61	0.072	0.005	0.078
GSM5	17	0.54	0.002	0.000	0.000
Total	105	0.538	0.00		0.507

Total number of data points (n): 5
 Degrees of freedom (n-1): 4
 Between machine sum of squares ($SS_{between}$): 0.507
 Between machine variance ($SS_{between} / dof$): 0.127

Analysis of Variance

Source of variation	Sum of Squares (SS)	Degrees of freedom (v)	Variance (s²)	Ratio of variance
Mean	56.49	1	56.49	
Between machines	0.507	4	0.127	1.160
Within machines	10.930	100	0.109	1.000
Total about grand mean	11.437	105		

The probability of a 1.16 or larger ratio using the F statistic with 4 and 100 degrees of freedom is 0.333.

Conclusion: Variance between GSM machines is statistically significant to the 66.7 % level. This is usually not significant enough to nullify the hypothesis that there is no significant differences between the machines.

Appendix B

Summary of feeder performance by machine

The following tables provide a summary of the component pick performance of each machine for the two time periods chosen. Each data point represents one half hour time period that the given feeder was used in production. The column labeled “Comp. picked” represents the number of pick attempts for the given feeder location. “Comp. placed” represents the number of successful pick attempts resulting in a component placed onto the board. The percent scrap is calculated as the number of components miss-picked as a percent of the number of components picked.

Machine: GSM1

Feb. 23 – April 8, 1998					
Feeder	Data Pts.	Comp. picked	Comp. placed	Scrap	% Scrap
F0001	186	7,118	7,093	25	0.35
F0008	186	7,132	7,093	39	0.55
F0014	43	2,752	2,742	10	0.36
F0037	899	57,981	57,874	107	0.18
F0039	186	7,249	7,096	153	2.11
F0041	581	33,453	33,082	371	1.11
F0101	900	58,061	57,891	170	0.29
F0103	365	26,260	26,065	195	0.74
F0105	316	17,808	17,714	94	0.53
F0108	211	8,955	8,886	69	0.77
F0111	308	19,067	18,990	77	0.40
F0114	179	7,224	7,190	34	0.47
F0123	553	31,976	31,773	203	0.63
F0125	302	18,011	17,819	192	1.07
F0128	470	25,153	24,861	292	1.16
F0134	332	14,255	14,070	185	1.30
F0137	301	11,804	11,652	152	1.29
F0140	157	5,539	5,494	45	0.81
F0143	154	10,193	10,138	55	0.54
F0146	327	23,415	23,312	103	0.44
F0149	18	453	449	4	0.88
F0157	36	1,151	1,137	14	1.22
F0160	17	256	247	9	3.52
F0166	150	10,524	10,463	61	0.58
F0169	36	2,694	2,685	9	0.33
Total	7,213	408,484	405,816	2,668	0.65

April 1 – June 30, 1998					
Feeder	Data Pts.	Comp. picked	Comp. placed	Scrap	% Scrap
F0001	319	14,223	14,190	33	0.23
F0008	319	14,263	14,189	74	0.52
F0014	145	9,312	9,264	48	0.52
F0037	1,756	138,974	138,732	242	0.17
F0039	319	14,226	14,192	34	0.24
F0041	52	4,113	4,092	21	0.51
F0044	1,006	72,718	72,486	232	0.32
F0101	1,760	139,145	138,702	443	0.32
F0103	781	67,506	67,318	188	0.28
F0105	650	44,580	44,316	264	0.59
F0108	431	23,341	23,151	190	0.81
F0111	614	43,767	43,609	158	0.36
F0114	404	23,934	23,798	136	0.57
F0123	1,024	73,105	72,800	305	0.42
F0125	594	38,885	38,623	262	0.67
F0128	468	27,650	27,484	166	0.60
F0131	911	55,737	55,228	509	0.91
F0134	688	36,299	35,958	341	0.94
F0140	328	14,198	14,070	128	0.90
F0143	319	28,539	28,411	128	0.45
F0146	701	58,104	57,850	254	0.44
F0149	3	436	433	3	0.69
F0157	56	3,291	3,262	29	0.88
F0160	30	1,154	1,127	27	2.34
F0163	11	543	541	2	0.37
F0166	278	21,884	21,745	139	0.64
F0169	76	4,543	4,502	41	0.90
Total	14,043	974,470	970,073	4,397	0.45

Machine: GSM2

Feb. 23 – April 8, 1998					
Feeder	Data Pts.	Comp. picked	Comp. placed	Scrap	% Scrap
F0002	66	4,361	4,352	9	0.21
F0005	5	140	140	0	0.00
F0008	135	11,605	11,567	38	0.33
F0014	269	11,686	11,650	36	0.31
F0032	302	13,466	13,388	78	0.58
F0034	35	1,850	1,846	4	0.22
F0035	5	422	420	2	0.47
F0037	473	33,238	32,814	424	1.28
F0039	473	32,942	32,809	133	0.40
F0041	975	62,805	62,719	86	0.14
F0044	899	58,085	57,784	301	0.52
F0101	980	63,090	62,944	146	0.23
F0103	78	4,644	4,633	11	0.24
F0105	74	3,989	3,963	26	0.65
F0108	112	6,409	6,365	44	0.69
F0111	74	4,257	4,243	14	0.33
F0114	97	5,716	5,696	20	0.35
F0121	3	81	80	1	1.23
F0123	901	57,984	57,772	212	0.37
F0125	12	397	392	5	1.26
F0128	80	4,606	4,551	55	1.19
F0131	104	4,245	4,208	37	0.87
F0134	44	2,561	2,547	14	0.55
F0137	372	21,375	21,245	130	0.61
F0140	258	11,555	11,493	62	0.54
F0143	16	593	590	3	0.51
F0146	16	594	591	3	0.51
F0157	314	15,122	15,030	92	0.61
F0160	424	29,867	29,773	94	0.31
F0163	198	8,086	8,041	45	0.56
F0169	56	3,060	3,044	16	0.52
Total	7,850	478,831	476,690	2,141	0.45

April 1 – June 30, 1998					
Feeder	Data Pts.	Comp. picked	Comp. placed	Scrap	% Scrap
F0001	11	250	244	6	2.40
F0002	84	5,666	5,652	14	0.25
F0004	13	362	360	2	0.55
F0008	112	8,148	8,128	20	0.25
F0010	70	6,128	6,116	12	0.20
F0012	69	3,916	3,849	67	1.71
F0014	365	16,251	16,210	41	0.25
F0015	76	7,561	7,528	33	0.44
F0021	123	7,364	7,325	39	0.53
F0031	15	749	734	15	2.00
F0032	427	19,403	19,292	111	0.57
F0034	97	4,543	4,512	31	0.68
F0037	441	32,908	32,606	302	0.92
F0038	369	23,138	23,077	61	0.26
F0039	441	32,704	32,604	100	0.31
F0040	356	22,783	22,711	72	0.32
F0041	1,019	63,656	63,556	100	0.16
F0042	331	16,289	16,210	79	0.48
F0044	1,655	100,188	99,539	649	0.65
F0101	1,426	84,831	84,574	257	0.30
F0103	208	11,436	11,370	66	0.58
F0105	133	6,839	6,804	35	0.51
F0106	803	49,445	49,168	277	0.56
F0108	575	58,871	58,661	210	0.36
F0110	22	1,059	1,052	7	0.66
F0111	148	7,951	7,919	32	0.40
F0112	74	5,287	5,252	35	0.66
F0114	182	11,609	11,572	37	0.32
F0115	745	43,349	43,265	84	0.19
F0121	344	22,040	21,918	122	0.55
F0123	932	57,371	57,200	171	0.30
F0124	402	20,595	20,547	48	0.23
F0125	13	489	477	12	2.45
F0126	748	43,362	43,265	97	0.22
F0128	438	23,469	23,312	157	0.67
F0131	140	6,143	6,096	47	0.77
F0134	76	3,435	3,420	15	0.44
F0137	348	20,954	20,826	128	0.61
F0138	693	54,738	54,421	317	0.58
F0140	281	13,738	13,644	94	0.68

GSM2 (continued)

April 1 – June 30, 1998

F0143	760	43,720	43,615	105	0.24
F0145	293	14,128	14,086	42	0.30
F0146	14	570	566	4	0.70
F0148	74	5,277	5,255	22	0.42
F0151	71	4,386	4,370	16	0.36
F0157	324	13,241	13,144	97	0.73
F0160	389	28,488	28,390	98	0.34
F0163	245	9,804	9,742	62	0.63
F0166	313	20,237	20,160	77	0.38
F0169	135	7,434	7,407	27	0.36
Total	17,423	1,066,303	1,061,751	4,552	0.43

Machine: GSM3

Feb. 23 – April 8, 1998					
Feeder	Data Pts.	Comp. picked	Comp. placed	Scrap	% Scrap
F0011	423	18,235	18,164	71	0.39
F0013	423	18,202	18,165	37	0.20
F0015	7	206	204	2	0.97
F0021	436	18,631	18,572	59	0.32
F0023	6	227	226	1	0.44
F0027	425	18,393	18,342	51	0.28
F0029	427	18,379	18,338	41	0.22
F0031	429	51,099	50,716	383	0.75
F0044	427	18,218	18,171	47	0.26
F0101	6	228	226	2	0.88
F0103	7	204	202	2	0.98
F0105	18	356	347	9	2.53
F0108	8	167	164	3	1.80
F0111	17	412	397	15	3.64
F0113	7	218	202	16	7.34
F0114	4	105	105	0	0.00
F0121	431	18,234	18,173	61	0.33
F0123	431	18,296	18,160	136	0.74
F0144	7	412	407	5	1.21
F0146	7	410	408	2	0.49
F0148	7	410	408	2	0.49
Total	3,953	201,042	200,097	945	0.47

April 1 – June 30, 1998					
Feeder	Data Pts.	Comp. picked	Comp. placed	Scrap	% Scrap
F0005	21	421	419	2	0.48
F0007	22	805	801	4	0.50
F0011	286	14,260	14,222	38	0.27
F0013	330	15,143	15,106	37	0.24
F0014	28	654	644	10	1.53
F0015	14	398	398	0	0.00
F0021	459	19,349	19,301	48	0.25
F0023	117	4,030	4,004	26	0.65
F0027	294	16,019	15,977	42	0.26
F0029	330	16,679	16,646	33	0.20
F0031	366	45,318	44,832	486	1.07
F0033	23	893	889	4	0.45
F0038	24	415	351	64	15.42
F0040	23	466	465	1	0.21
F0042	41	794	788	6	0.76
F0044	336	14,942	14,922	20	0.13
F0101	70	2,593	2,573	20	0.77
F0103	127	3,998	3,902	96	2.40
F0105	75	2,339	2,293	46	1.97
F0107	32	678	642	36	5.31
F0108	75	2,193	2,108	85	3.88
F0110	31	644	644	0	0.00
F0111	29	860	856	4	0.47
F0114	13	522	520	2	0.38
F0121	362	16,056	15,999	57	0.36
F0123	313	14,708	14,630	78	0.53
F0125	16	536	532	4	0.75
F0128	10	359	357	2	0.56
F0131	16	372	369	3	0.81
F0134	13	523	520	3	0.57
F0137	24	891	889	2	0.22
F0160	35	387	381	6	1.55
F0163	16	321	317	4	1.25
F0166	21	422	418	4	0.95
Total	3,992	198,988	197,715	1,273	0.64

Machine: GSM4

Feb. 23 – April 8, 1998					
Feeder	Data Pts.	Comp. picked	Comp. placed	Scrap	% Scrap
F0014	104	3,003	2,979	24	0.80
F0021	2	395	391	4	1.01
F0030	106	3,415	3,368	47	1.38
F0033	303	26,526	26,452	74	0.28
F0037	182	25,954	25,696	258	0.99
F0039	78	4,874	4,834	40	0.00
F0041	77	6,246	6,224	22	0.35
F0044	967	82,919	82,786	133	0.16
F0101	967	82,931	82,781	150	0.18
F0103	15	1,111	1,018	93	8.37
F0121	965	82,361	82,216	145	0.18
F0123	953	82,827	81,671	1,156	1.40
F0131	105	6,308	6,240	68	1.08
F0134	92	4,943	4,906	37	0.75
F0137	353	28,136	27,903	233	0.83
F0140	391	33,913	33,798	115	0.34
F0149	20	1,179	1,169	10	0.85
F0157	420	32,615	32,402	213	0.65
F0160	79	4,876	4,834	42	0.86
F0163	179	10,270	10,209	61	0.59
F0166	127	9,849	9,818	31	0.31
Total	6,485	534,651	531,695	2,956	0.55

April 1 – June 30, 1998					
Feeder	Data Pts.	Comp. picked	Comp. placed	Scrap	% Scrap
F0011	11	624	623	1	0.16
F0014	168	5,809	5,771	38	0.65
F0030	168	5,887	5,770	117	1.99
F0033	568	52,829	52,670	159	0.30
F0037	444	60,554	60,003	551	0.91
F0039	278	19,837	19,582	255	1.29
F0041	140	10,216	10,183	33	0.32
F0044	1,764	151,028	150,702	326	0.22
F0101	1,777	151,648	151,311	337	0.22
F0103	11	443	435	8	1.81
F0105	10	510	505	5	0.98
F0108	7	122	118	4	3.28
F0111	4	130	130	0	0.00
F0114	10	494	493	1	0.20
F0121	1,775	151,054	150,716	338	0.22
F0123	1,765	152,764	150,639	2,125	1.39
F0125	7	280	280	0	0.00
F0128	7	344	343	1	0.29
F0131	191	12,236	12,152	84	0.69
F0134	167	8,829	8,752	77	0.87
F0137	610	46,284	45,939	345	0.75
F0140	604	51,078	50,897	181	0.35
F0143	4	189	188	1	0.53
F0157	762	54,099	53,702	397	0.73
F0160	280	19,695	19,575	120	0.61
F0163	539	32,066	31,837	229	0.71
F0166	245	19,674	19,594	80	0.41
Total	12,316	1,008,723	1,002,910	5,813	0.58

Machine: GSM5

Feb. 23 – April 8, 1998					
Feeder	Data Pts.	Comp. picked	Comp. placed	Scrap	% Scrap
F0001	443	27,354	27,289	65	0.24
F0003	412	24,932	24,825	107	0.43
F0005	141	9,144	9,102	42	0.46
F0008	880	104,994	104,620	374	0.36
F0021	114	25,469	25,345	124	0.49
F0023	118	29,910	29,782	128	0.43
F0025	3	4	4	0	0.00
F0030	490	26,871	26,822	49	0.18
F0032	364	42,273	42,129	144	0.34
F0034	13	2,325	2,318	7	0.30
F0037	182	10,614	10,477	137	1.29
F0039	32	2,470	2,464	6	0.24
F0041	422	25,075	25,025	50	0.20
F0043	435	26,656	26,481	175	0.66
F0045	424	25,078	25,023	55	0.22
F0047	444	27,334	27,258	76	0.28
F0049	2	2	2	0	0.00
F0051	126	6,923	6,884	39	0.56
F0101	48	2,035	2,010	25	1.23
F0104	36	1,520	1,498	22	1.45
F0107	227	10,526	10,415	111	1.05
F0110	147	5,208	5,131	77	1.48
F0113	111	4,552	4,506	46	1.01
F0121	62	3,048	3,020	28	0.92
F0130	208	9,565	9,502	63	0.66
F0133	148	6,499	6,456	43	0.66
F0137	60	2,752	2,734	18	0.65
F0140	109	6,204	4,582	29	0.47
F0143	38	1,350	1,334	16	1.19
F0146	22	837	828	9	1.08
F0164	11	150	146	4	2.67
Total	6,272	471,674	468,012	2,069	0.44

April 1 – June 30, 1998					
Feeder	Data Pts.	Comp. picked	Comp. placed	Scrap	% Scrap
F0001	804	44,583	44,474	109	0.24
F0003	766	42,697	42,393	304	0.71
F0005	243	13,220	13,131	89	0.67
F0008	1,578	170,649	169,733	916	0.54
F0021	221	42,852	42,650	202	0.47
F0023	229	47,189	46,974	215	0.46
F0025	7	5	4	1	20.00
F0027	5	4	4	0	0.00
F0030	890	44,649	44,546	103	0.23
F0032	650	69,219	68,950	269	0.39
F0034	46	5,292	5,189	103	1.95
F0037	377	19,574	19,335	239	1.22
F0039	41	2,088	2,081	7	0.34
F0041	797	42,450	42,359	91	0.21
F0043	783	43,611	43,525	86	0.20
F0045	795	42,455	42,352	103	0.24
F0047	800	44,537	44,438	99	0.22
F0049	2	1	1	0	0.00
F0051	245	11,219	11,192	27	0.24
F0101	92	3,980	3,945	35	0.88
F0104	56	1,728	1,705	23	1.33
F0107	419	16,245	16,039	206	1.27
F0110	325	12,460	12,321	139	1.12
F0113	154	6,069	5,975	94	1.55
F0121	105	3,648	3,604	44	1.21
F0130	444	19,845	19,705	140	0.71
F0133	225	8,856	8,788	68	0.77
F0137	100	4,268	4,242	26	0.61
F0140	189	8,203	8,145	58	0.71
F0143	43	1,508	1,493	15	0.99
F0146	25	675	670	5	0.74
F0160	7	16	14	2	12.50
F0164	15	407	402	5	1.23
F0167	7	287	284	3	1.05
Total	11,485	774,489	770,663	3,826	0.49