

Application of Statistical Quality Control to Improve Yields and Rationalize Testing in a Low Volume Manufacturing Facility

by

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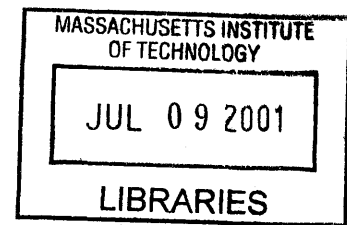
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Submitted to the Sloan School of Management and the Department of Civil and Environmental Engineering on May 5, 2001 in Partial Fulfillment of the Requirements for the Degrees of Master of Science in Management and Master of Science in Civil and Environmental Engineering

Abstract

Qualcomm's Wireless Business Solutions group manufactures two-way satellite communications systems for the commercial trucking industry at its facilities in San Diego. The testing process for this family of products, called OmniTRACS, is sub-optimal. First-pass yields for the entire test process average 60%, but most of the failed units pass upon retest. Tens of thousands of dollars are wasted each year on additional testing and debug efforts for these units that are ultimately shipped without any rework. This thesis describes the efforts of a yield improvement team chartered to increase first-pass yields dramatically throughout the test process.

The yield improvement team utilized statistical control charts and Gage Repeatability and Reliability studies to better understand the nature of process failures at the final test step and the capability of the test process itself. This knowledge enabled the team to eliminate non-value added tests and increase some arbitrary specification limits. Yields at the final test step increased from 88% to 97%, generating a projected annual savings of more than \$45,000.

Increased visibility of process performance at the final test step was a necessary prerequisite to the process change, so the team developed a decision support tool that enables continuous monitoring of process performance at any test step in the OmniTRACS manufacturing process. The tool should enable future process improvements at other test steps by providing the statistical data necessary to guide process changes.

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1.0 INTRODUCTION

The testing process for OmniTRACS Antenna Communications Units (ACU's) at Qualcomm's manufacturing facility in San Diego was sub-optimal. First-pass yields for the entire test process averaged 60%, but most of the failed units pass upon retest. Tens of thousands of dollars were wasted each year on additional testing and debug efforts for these units that were ultimately shipped without any rework.

Statistical Process Control (SPC) has been used effectively in the manufacturing industry to improve quality and reduce costs. But SPC is not a silver bullet. It is not a tool that you buy off the shelf, turn on, and magically generate improvement in your manufacturing process. Rather, implementing SPC is a process of discovery and experimentation. It requires the proper resources, including tools and training, to be used effectively within an organization.

This thesis describes the effort undertaken by a process improvement team within Qualcomm's Wireless Business Solutions (QWBS) division to begin using statistical process control tools to improve manufacturing yields. Over a period of six months, the team was able to improve yields from 88% to 97% at the final test step in the process, resulting in an annual savings of approximately \$45,000. The knowledge the team gained through the effort and the tools it developed to support the change should enable future improvements, as well.

1.1 Project Description

QWBS management recognized the need to improve its test procedures in order to increase factory yields and reduce manufacturing costs. An internship proposal was submitted to the Leaders for Manufacturing Program that contained three related, yet distinct potential projects:

1. Reduce/eliminate non-value added testing
 - Use statistical analysis to predict field performance of units based on factory parametric test results.

- Conduct experiments by shipping units that have not undergone specific tests and measure performance relative to the general population.
2. Correlate factory parametric test data, factory Can Not Duplicate (CND) rates, and Return Material Authorization (RMA) rates
 3. Create an on-line SPC system for displaying real-time statistical analysis

1.2 Project Approach and Methodology

The efforts to improve yields and increase factory efficiency were focused on two parallel paths:

1. How the product is tested (process capability, tester capability).
2. What product attributes are tested (Are the right attributes being tested? Is there any correlation between factory test results and field performance?)

Following is a more detailed description of each path.

How the Product is Tested

The first step of the internship was to characterize the current test process from a statistical standpoint. I analyzed historical test results to understand the central tendency and variation of each test attribute on each test station. I then compared the results to specification limits to understand process capability. I also helped design and perform Gage Repeatability and Reliability (Gage R&R) tests to determine the measurement capability of key test equipment.

Once I understood the capability of the test process, I combined this knowledge with historical test failure data to help explain the high rate of Can Not Duplicate (CND's) seen in the product testing. This allowed the group to focus on improving and/or eliminating the most problematic tests from the process, with the goal of reducing the wasted effort of retesting and debugging "good" units.

Correlate Factory Test Results with Field Performance and Returned Units

The ultimate goal of product testing in the factory is to improve the quality of units in the field. Many tests were developed over time to simulate in the factory the products'

operational environment, but there were no data indicating whether the unit performance in factory tests correlated in any way with unit performance in the field. The goal of this effort was to collect and analyze field performance data to help make the determination whether the current suite of factory tests are useful indicators of field quality.

A wealth of over-the-air field performance data is collected at Qualcomm's Network Management Centers (NMC's) in San Diego and Las Vegas. All messages sent to and received by the OmniTRACS units in the field are routed through one of the two NMC's, and performance metrics are available for each transmission. However, utilizing this data proved more difficult than anticipated. The data is spread across thousands of text files, making it difficult to aggregate for analysis. Qualcomm also has a policy in effect and contractual agreements with its customers that address how long data may be store by Qualcomm.

An NMC operator developed a batch routine to pull the desired data from the different text files, but the process was not completed until the end of the internship. We were therefore unable to collect enough data to perform a meaningful analysis.

Developing a Software Tool to Support Process Analysis

In addition to a set of analyses and recommendations, a further goal of the internship was to develop a set of software tools to enable future analysis and monitoring of the health of the manufacturing process. The organization had no clear vision of what the tool should look like or the capabilities it should possess. So I worked on my own to recognize the latent requirements for statistical data within the organization and then to develop a tool that would address those needs.

Yield Improvement Team

A cross-organizational and cross-functional Yield Improvement Team had been created prior to the internship to drive improvements in the OmniTRACS test process. The internship was proposed in part to provide the team a dedicated resource to collect and analyze test data and to introduce the team to statistical process control concepts and

practices. All decisions regarding resource allocation and process changes associated with the project were made by the team.

2.0 PROJECT SETTING AND BACKGROUND

2.1 Company Background, Position, and Outlook

Qualcomm's Wireless Business Systems (QWBS) is a division of Qualcomm, Incorporated that manufactures two-way satellite communications systems for the commercial trucking industry. QWBS is the largest player in the market with more than 350,000 OmniTRACS units in the field. More than 1,200 U.S. fleets utilize OmniTRACS, including 37 of the top 40 truckload fleets in the country. QWBS also has a strong presence in Mexico, Brazil, Argentina, Canada and Europe, and it is actively trying to penetrate the potentially vast Chinese market.

Despite its strong position in the market, QWBS has set an aggressive growth target known as the 2 x 4 plan: to double both revenue and profitability in four years. But a softening of the commercial trucking market and increased competition have amplified the cost pressures on QWBS. Historically, reductions in product cost were achieved through material price reductions from suppliers. However, suppliers can only be squeezed so far, and additional cost reductions need to be generated through improvements in manufacturing efficiency in order to meet the 2 x 4 plan.

QWBS competes in its market primarily based on quality and technology. It offers customers immediate replacement of units that fail in the field; sometimes new units are shipped to customers before the failed units are received.

As a result, an attitude exists within the division that no product should ship without complete confidence in its ability to perform. Unfortunately, the product was designed more than ten years ago, and many aspects of the design have very little margin. Quality has become an attribute that is tested into the product, as opposed to being *designed* into the product.

A potential conflict between product quality and manufacturing efficiency was thus exposed, as efforts to reduce test times and improve test effectiveness became more

critical. Two camps developed. One argued that the test process was inefficient and used historical data on failure modes to show the wastefulness of some test steps (the primary failure mode was CND). The other camp replied that low product return rates showed that the test process was effective, and that any efforts to experiment with changes to the test process risked alienating the customer base. No progress was made because no proposals were developed that addressed the needs of both groups.

But there was incentive to change. Coincident with the push to improve manufacturing efficiencies in QWBS's San Diego facility was a move toward outsourcing newer products to contract manufacturers in Mexico. There were no stated plans to ultimately outsource the Omni product, but employees in the San Diego facility recognized that future potential. This added to the support for change.

2.2 Organizational Skills

The two key groups involved in the project, the Quality group and the Test Engineering group, had completely different sets of skills. The Quality group consisted primarily of mechanical engineers, some of whom were familiar with the general concepts of statistics. But they used their knowledge to monitor and improve the process only on an ad-hoc basis. One engineer analyzed process data every two to three months to understand the process capability. Another engineer developed a set of Gage R & R experiments to understand the measurement capabilities of some new test equipment. The engineers spent most of their time fighting fires, and the engineers who understood statistics used their knowledge to help them fight fires more effectively.

The Test Engineering group consisted primarily of software programmers. They developed the hardware and software used to test the products. According to the group manager, the group lacked even basic knowledge of statistics and the concept of variability.

2.3 Information Technology

QWBS utilized a variety of software applications to run its manufacturing operation. Production control was managed through a home grown system called Shop Floor Control (SFC), which is based on an unsupported version of an Oracle database. The organization was evaluating options for upgrading the system, which included upgrading to Peoplesoft, upgrading to a supported Oracle database, or continuing to support the existing database. Development on the platform had been restricted to maintenance until a decision on the future of the application was made.

Finished goods inventory, customer shipments, and product returns data were maintained on a Peoplesoft database. There was no automated interface between Shop Floor Control (SFC) and Peoplesoft.

Parametric test results were stored in a Microsoft Access database called QualityLink. Each tester generated text files containing the results of the most recent test. A routine ran continuously that pulled those text files into an Access database where they could be analyzed off-line. There were no interfaces between QualityLink and SFC, nor between QualityLink and Peoplesoft.

This led to some inconsistencies in reports used to evaluate quality metrics. Quality data in SFC were entered manually by operators on the floor at the conclusion of each test. Error codes were selected from dropdown boxes, but there was no safeguard against the selection of an incorrect code. Yield reports were generally generated from SFC. Quality data in QualityLink were generated automatically by the test software, so it was generally guaranteed to be accurate. However, the part number of the unit under test was manually input by the operator before each test, and there were no safeguards against the input of an incorrect part number. Part numbers were input before each successive test, so it was possible to have the part number of a unit change from one test to the next. QualityLink data was used primarily for ad-hoc analysis. Canned quality reports using QualityLink data had not been developed.

I believed it feasible to develop new functionality for the QualityLink system. The database was managed by an engineer in the Test Engineering organization, and he was willing to grant me administrative access to the database.

Development of a new suite of software (called Common Test Software, or CTS) to manage the test systems was almost complete when I arrived. Since it was still under development, I could have focused my efforts on adding a statistical process control module to the system. However, implementation of CTS was scheduled on only the new product lines QWBS was developing. Converting the existing OmniTRACS test process code to CTS would basically require a complete rewrite (a significant effort on the behalf of the Test Engineering group) and the possibility that OmniTRACS manufacturing could be outsourced within two years led QWBS management to de-prioritize the investment. Since virtually 100% of manufacturing's volume consisted of OmniTRACS products, it didn't make sense to pursue CTS.

3.0 THE OMNI TEST PROCESS

3.1 Satellite Communications Overview

The OmniTRACS product provides two-way satellite communications for the commercial trucking industry. As shown pictorially in Figure 1, Integrated Mobile Communications Terminals located on trucks communicate with a Network Management Center (NMC) run by Qualcomm through a system of satellites. The NMC communicates with the trucks' fleet management office through whatever medium the customer requests (Internet, phone line, etc.). Services include text messaging, position tracking (akin to GPS), and integration capability with other applications, such as route planning, dispatch and accounting. Additional hardware options allow the customer to track trailers and to monitor driver and vehicle performance (mpg average, overrev and override data). Unlike most cellular-based systems, nationwide coverage is seamless.

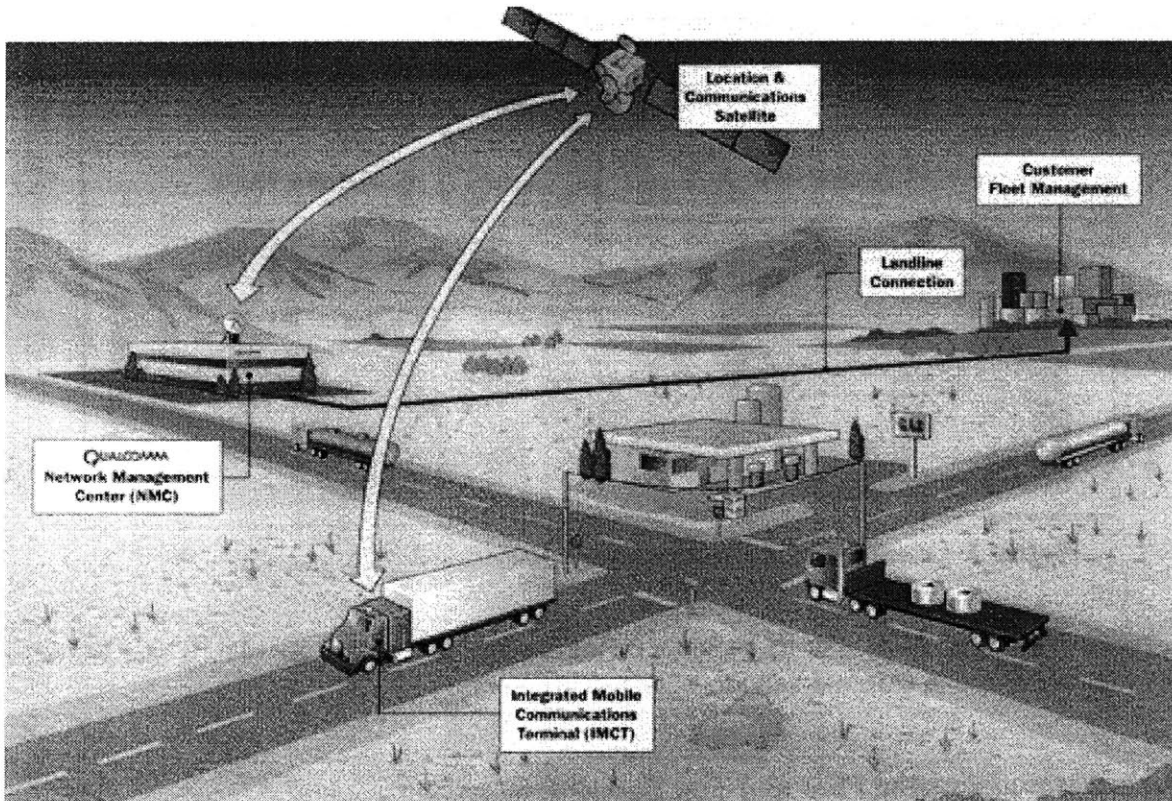


Figure 1 Satellite Communications Overview

3.2 Product Overview

QWBS manufactures several products at its San Diego facility. Its most mature product, the OmniTRACS, comprises most of the plant's volume and was the focus of the yield improvement efforts.

The OmniTRACS product consists of two separate units, as seen below in Figure 2. The Antenna Communications Unit (ACU) sits atop the truck cab and communicates with the satellite. The display unit (DU), or enhanced display unit (EDU), sits inside the cab and allows the driver to send and view messages.

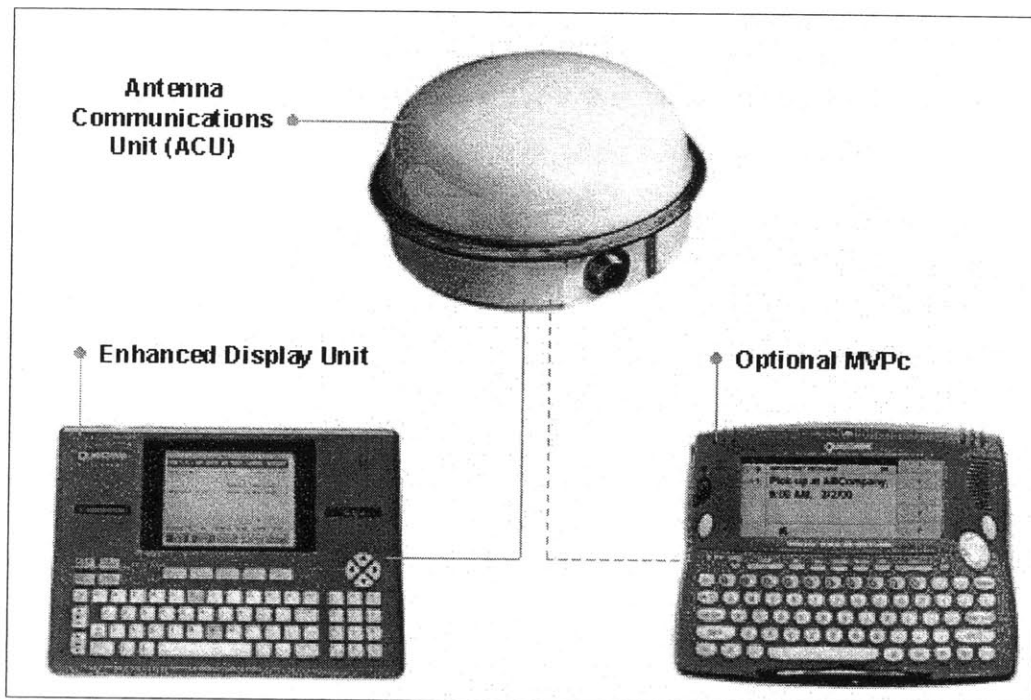


Figure 2 OmniTRACS Product Overview

QWBS assembles ACU's in its manufacturing facility in San Diego. DU's and EDU's are sourced from an external vendor.

3.3 Manufacturing Flow and Test Description

The ACU manufacturing process consists of about 20 minutes of assembly and 20 hours of testing. Figure 3 shows the flow of the assembly and test operations. Three different types of circuit cards - analog, digital, and RF - each go through a functional test before

assembly into the “dog bowl,” or the metal housing of the ACU that then becomes the centerplate. Once the three cards and a power supply are installed, the unit goes through a functional test called Centerplate Functional. The centerplate is then tested on a vibration table at the Vibe station. Next, the centerplate is tested at +70°C and –30 °C at the Environmental test. The unit is then subjected to an eight-hour burn-in process, during which it is tested multiple times. After burn-in, an antenna is installed and then the unit is tested over the air at the final test step, Acceptance Test Procedure (ATP).

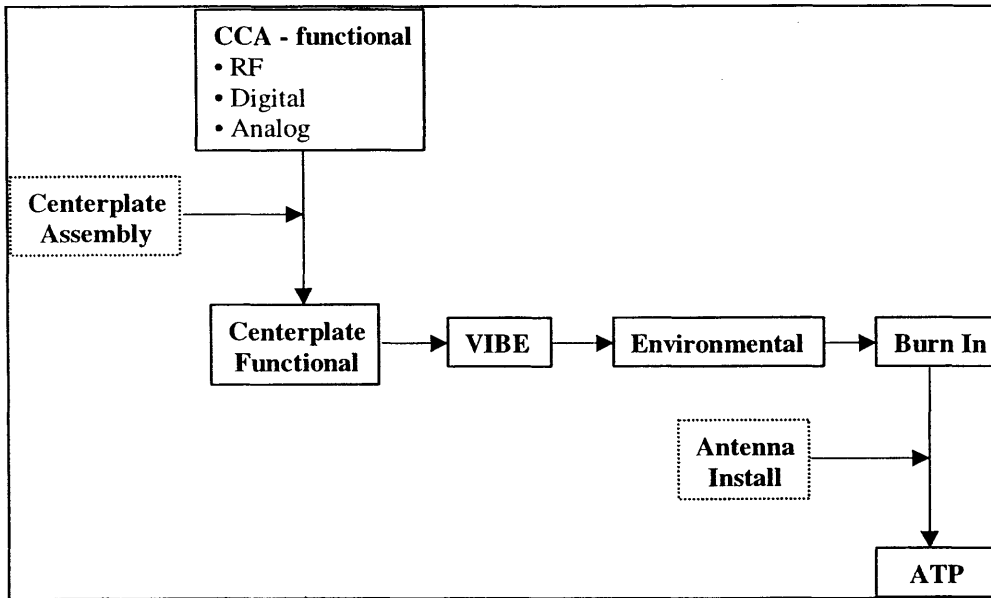


Figure 3 OmniTRACS Test Process Flow

Following is a more detailed description of each test step.

3.3.1 Centerplate Functional

The centerplate functional test performs a series of electrical tests to verify parametric performance of several attributes across the relevant frequency band. Gain and noise figure are measured at each frequency to ensure they fall within an acceptable range. Transmit power, phase noise, and spurious emissions are measured and checked against allowable limits. Signals are sent and received through a direct electrical connection between the unit and the tester. The test has a batch size of one and it takes approximately 5 minutes to perform.

Failure rates at centerplate functional are fairly low (First-pass Yield = 93%), and the failures that are found are typically repeatable and real. The highest rate of CND failures for any single test attribute was only 0.14%.

3.3.2 Vibe

The vibe test is designed to simulate the vibrational conditions the unit may experience in the field while attached to a moving truck. During the test, the unit sends and receives messages directly through an electrical connection to the test station while undergoing acceleration on a vibration table. Signal-to-noise ratios (forward link, return link, and ranger, or positioning link) are measured and checked against the specification limits. A host of additional metrics are evaluated, as well. The test has a batch size of 1 and it takes approximately 8 minutes to perform.

Failure rates at Vibe are relatively low (FPY = 92%), but the rate of CND's is high. Nearly 94.5% of the failures recorded for the top five failure modes were not repeatable.

3.3.3 Environmental

The environmental test performs the same electrical tests that are performed at centerplate functional, except the tests are performed at temperature extremes. The test has a batch size of 40 and it takes 6 hours to complete (so the processing time per unit is about 15 minutes).

Failure rates at environmental are high (FPY=82%), but for the most part the test is catching real failures. Of the four failure modes with the highest CND rates, only 35% of the total failures are CND's.

3.3.4 Burn-in

The burn-in test (generally called Ransco, after the manufacturer of the test chamber) performs messaging tests while cycling the units through a series of temperature swings. While the message test itself is the same as the one performed at vibe, there are some

technical differences in how the unit communicates with the test station that make the test more complex. The batch size of a Ransco chamber is 250 units and the test takes 12 hours to complete. Note that the test time is not reduced if fewer units are run. Each unit is just tested more frequently over the 12-hour burn-in cycle.

There is some debate within the organization over the purpose of the Ransco test. The original intent of the test was three-fold:

1. Screen for infant mortality
2. Screen for intermittent failures
3. Perform some tests that aren't performed anywhere else in the test process

The quality group believed that Ransco did not effectively perform any of the above functions and it wanted to eliminate the test entirely. Unfortunately, no tests had been designed to measure Ransco's effectiveness at meeting the three aforementioned objectives.

The available data - failure data - showed that Ransco had a reasonably low failure rate (FPY = 92%), but that the CND rate was high. Of the four failure modes with the highest CND rates, 77% of the failures were not repeatable.

3.3.5 Acceptance Test Procedure

The Acceptance Test Procedure (ATP) performs the same basic messaging test that is performed at vibe and Ransco, except the test is performed over the air. Just before ATP, the antenna is installed, so the ATP test checks to see if the unit can acquire a signal and send and receive messages from a simulated satellite within the factory. Signal-to-noise ratios are again the primary metrics of interest. The batch size of the ATP test is 1 and the test takes approximately 8 minutes.

Failure rates at ATP are high (FPY = 88%), and nearly 100% of the units that fail ultimately pass without rework.

4.0 Improving How Existing Tests Are Performed

4.1 Yield Improvement Team

Before the internship began a yield improvement team with four goals was created:

- Improve yields (95% First-pass Yield at each test step)
- Lower product cycle time
- Improve quality
- Understand CND failures

The team had collected yield information for each test step in the process and determined that improving the ATP step would provide the most benefit for the effort. While first-pass yields at ATP were not the lowest of all of the tests, the rate of CND failures was extremely high. Eliminating most of the CND's would reduce the wasted effort that went into multiple retests of product that ultimately was shipped without any rework. Table 1 summarizes the first-pass yield and CND rates for each test step.

Test Step	First-pass Yield	CND as % of Failures	CND as % of Total Tests
ATP	88%	99%	11.9%
Vibe	92%	94%	7.5%
Environmental	82%	35%	6.3%
Ransco	92%	77%	6.2%
Centerplate Functional	93%	0.14%	1%

Table 1 CND Rate by Test Step

The data in Table 1 actually underestimate the true impact of CND's on process efficiency. Units that fail at Centerplate Functional, Vibe, and ATP are immediately retested. Units that fail upon retest are sent to a debug station where a technician evaluates them. If the failure can not be duplicated by the technician, then the unit is sent back to the test station. Some units are tested and retested up to eight times before ultimately passing (a unit passes a test if it successfully completes one test cycle without failure, irrespective of the number of prior failures). These retests are not completely

captured in the above table. Over one two-month time frame, the CND rate as a function of total tests equaled 21%.

Sorting the data by cost of each CND or by greatest pain to the organization would have been useful in assessing the areas of greatest impact, but we were unable to collect the data necessary to perform these rankings.

During my internship I became the primary resource dedicated to collecting and analyzing data for presentation to the yield improvement team. Building on the work done by the team, I chose to focus first on the ATP process.

4.2 Characterizing the Current State of the Process

The first step in improving a process is to determine the current state, or the baseline. Many different types of analyses are useful in characterizing process performance. Perhaps the most common analysis, and the one predominantly used within QWBS, is the pareto chart.

While pareto charts are useful in focusing attention on the most frequently occurring or most costly failure modes, they don't provide any insight into why failures might be occurring. They contain no information on the statistical distributions of the test results. Two additional tools that are helpful in understanding process performance are control charts and Gage R&R studies. Control charts capture the dynamic nature of the process, and they include a measure of variability. Gage R&R studies provide insight into the sources of variability.

Following is a discussion of how we used each tool to better understand the performance of the OmniTRACS test systems.

4.2.1 Pareto Diagrams of Failure Modes

The quality group generated yield and failure reports on a weekly basis that were reviewed at a staff meeting. Figure 4 shows an example of a run chart of weekly yields for the ATP test step.

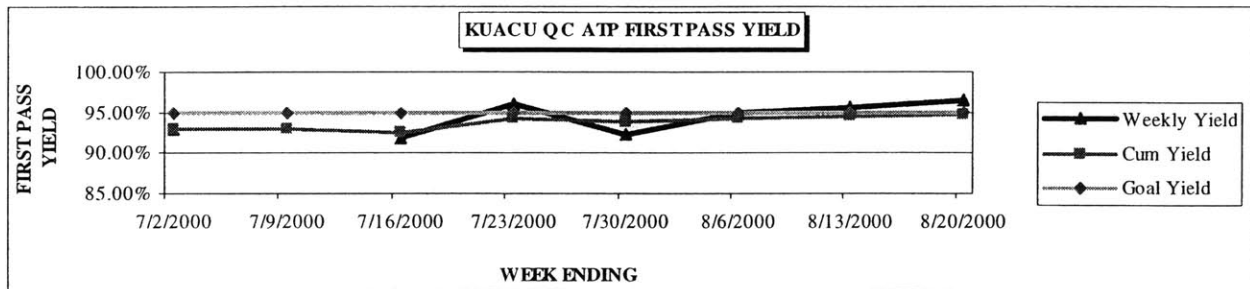


Figure 4 Weekly Yield Summary Report

By drilling down into the report, the distribution of failures across failure modes was available. Figure 5 shows an example of the detailed failure data table.

Operation	Qualifier	7/2	7/9	7/16	7/23	7/30	8/6	8/13	8/20	Cum Total
ATP_TEST	QSSE0	14	0	7	4	4	19	11	4	63
	QSRD1	8	0	3	4	4	8	2	3	32
	RMRE1	1	0	3	2	7	3	6	0	22
	RMTO0	1	0	1	4	8	5	0	2	21
	RMTO2	3	0	2	7	3	1	2	3	21
	QSRD0	5	0	2	0	1	2	0	0	10
	FMM01	0	0	0	2	1	2	2	0	7
	GPERR	0	0	1	2	1	2	0	1	7
	SWWK1	1	0	0	3	1	0	1	0	6
	OVOT2	0	0	0	1	0	2	1	1	5
Qualifier Totals		33	0	19	29	30	44	25	14	194

Figure 5 ATP Failure Mode Pareto

The data in Figure 5 include both real failures and CND's. Since the goal of the internship was to reduce/eliminate CND's, I generated a pareto of CND failures by failure mode. The results, shown in Figure 6, reveal that the top nine failure modes (out of a total of 33) account for 80% of the CND failures.

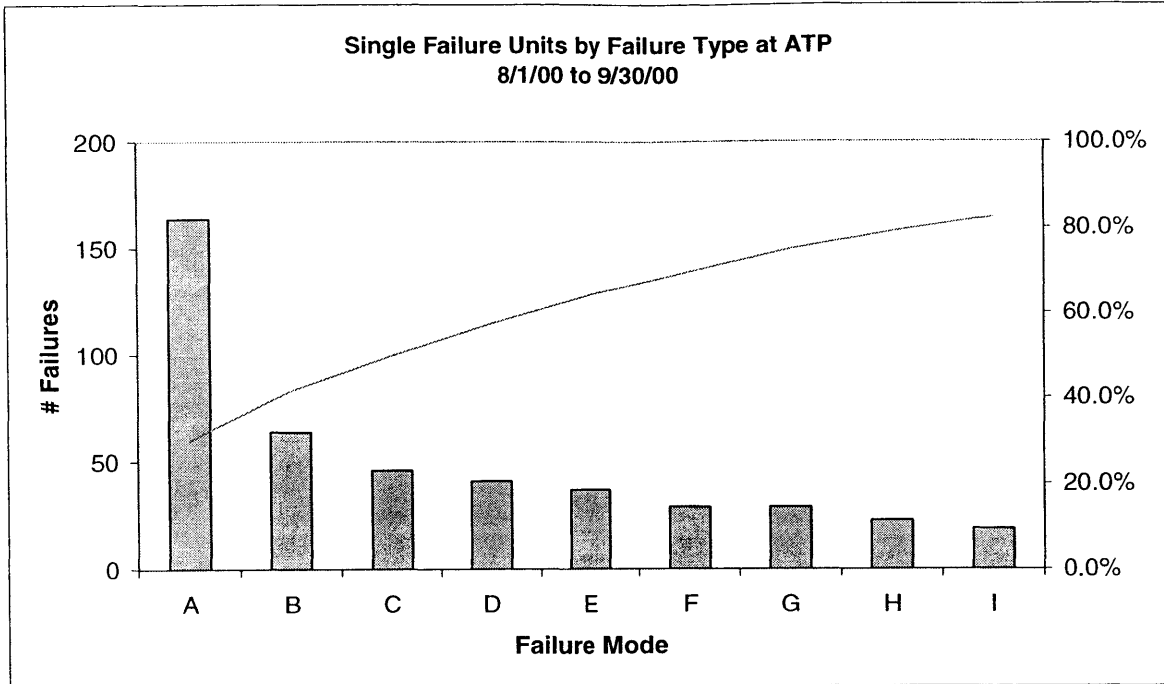


Figure 6 ATP CND Failure Pareto

With the CND problem distilled down to a manageable set of test attributes, the focus was then to identify the source of those failures.

4.2.2 Understanding Process Capability at ATP

The goal of statistical quality control is to understand the sources of variation in a process. Variation can come from one of two sources: assignable causes; and natural variation. If a process is operating without the presence of assignable causes, then it is in a state of statistical control.

However, whether a process is in control or not does not determine how many failed units the process might generate. The relationship between the process mean and variability, and the product or test specification limits determines the expected rate of failures. This relationship is usually expressed as a process capability index, or Cpk.

$$C_{pk} = \min\left(\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right)$$

where USL = Upper Specification Limit and LSL = Lower Specification Limit

As the capability ratio decreases, the number of failures you expect to see in the absence of assignable causes increases. This reveals several areas of inquiry necessary to determine why units might be failing a process.

1. Is the process centered? If the process mean is close to either the lower or upper specification limit, the capability ratio may become unacceptably small, even if the process is in a state of statistical control.
2. Is the process variability large?
3. Is their significant variability in the measurement process?

To answer the question of why seemingly good units were failing at ATP, we wanted to answer the three questions above. We also needed to determine whether the process was operating in a state of statistical control (without assignable causes).

Data collection was not an issue. All test results are automatically logged into a database to which I had access. In fact, the volume of available data presented more of a challenge than anything else. More than 50 attributes were tested on each product at ATP, and five different product variations were consistently produced. To make the analysis feasible, we chose to focus first on the highest volume part number. We also leveraged our findings from the pareto analysis of CND defect rates by attribute to limit our study to the top five test attributes of concern.

In order to get meaningful results, we also had to segment the data further. ATP tests were performed on four different tools, each with potentially different performance characteristics. Thus we had to perform the analysis on each tool separately. Also, the selected part number could contain one of two centerplates, one produced by QWBS or one purchased from an outside vendor. We broke the data into these two sub populations so we could see any performance differences between the two.

Figure 7 summarizes the process capability of each ATP test station for the three signal-to-noise ratios evaluated during the test.

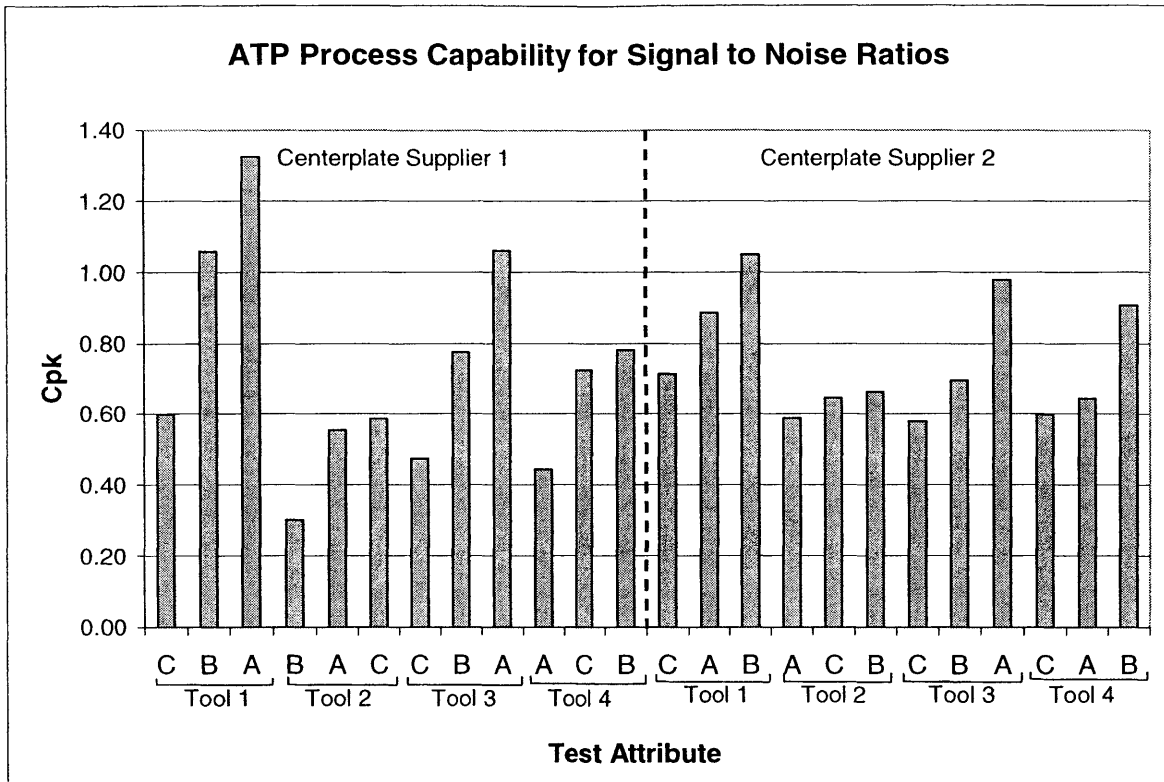


Figure 7 ATP Process Capability for Signal-to-Noise Ratios

The process capability ratio (Cpk) can be used to estimate expected fallout from the process in the absence of assignable causes. We can use this fact to determine whether the process capability ratios exhibited in Figure 7 explain the high rate of CND's at ATP. To do so, I used the Cpk of each attribute-tool-centerplate combination to look up an expected fallout rate and then weighted each fallout rate by the ratio of the number of attribute-tool-centerplate tests to the total number of tests. Performing this calculation for the three signal-to-noise ratios leads to an expected fallout rate of 2.3% (see appendix for a detailed summary of this calculation).

The process capability analysis reveals that the ATP process will have relatively high fallout rates, even when the incoming product may have nothing wrong with it. There are then four levers that can be used to improve process capability and reduce the fallout rate:

1. Center the process mean.
2. Reduce process variability.
3. Increase the specification limits.
4. Reduce the variability in the measurement process.

If the mean were exactly centered between the existing specification limits without changing the variability, expected fallout for the three signal-to-noise ratios would fall from approximately 2.3% to 1.5%. Changing the specification limits from +3dB and –2dB to +5dB and –5dB leads to an expected fallout of only 0.6%. Reducing variability would have a similar affect, depending on the magnitude of the change.

4.2.3 Gage Repeatability and Reliability Study on ATP

Gage R&R studies are designed experiments that measure the variability of a measurement process, including both operator variability and gage (or test equipment) variability. Characterizing how much of the total variation in the ATP test measurements was due to the test process itself (as opposed to the product) was essential to the improvement process.

The standard Gage R&R study involves the measurement of a group of parts (typically around 10) multiple times (two or three) by multiple operators. Measuring 10 different parts allows you to calculate variation across parts. Measuring the same part multiple times allows you to calculate variation in the measurement. Measuring the same part by different operators allows you to calculate the variation introduced by the test operators.

The experiment we performed at ATP included eight parts, two operators, and three trials per part per operator. The resulting data collection form is displayed in Figure 8 (on the next page).

Appraiser	Trial	Part							
		1	2	3	4	5	6	7	8
		A	1						
	2								
	3								
B	1								
	2								
	3								

Figure 8 Gage R&R Data Collection Sheet

Because the test process is automated, it was not expected that the operator variability would be significant. The experiment was not too costly to run, though, so we included the second operator to test the hypothesis.

The experiment was run on each ATP test station. We did not run the test separately for each centerplate supplier, but the only difference should be in the part variation, which was not the focus of the experiment. The results of the experiment are listed in Table 2 below.

Test Station	Parameter	% EV	% AV	% Gage RR	% PV	Gage Acceptability
Tool 1	A	92.2%	0.0%	92.2%	38.8%	0.72
Tool 1	B	54.1%	0.0%	54.1%	84.1%	0.46
Tool 1	C	13.0%	0.0%	13.0%	99.1%	0.08
Tool 2	B	72.3%	0.0%	72.3%	69.1%	0.55
Tool 2	A	86.1%	0.0%	86.1%	50.9%	1.30
Tool 2	C	54.9%	0.0%	54.9%	83.6%	0.38
Tool 3	B	56.1%	0.0%	56.1%	82.8%	0.51
Tool 3	A	90.0%	0.0%	90.0%	43.6%	0.67
Tool 3	C	67.7%	0.0%	67.7%	73.6%	0.53
Tool 4	A	75.7%	0.0%	75.7%	65.4%	0.56
Tool 4	B	51.9%	0.0%	51.9%	85.5%	0.35
Tool 4	C	35.2%	0.0%	35.2%	93.6%	0.31

Table 2 ATP Gage R&R Results

Percent EV (equipment variation), % AV (appraiser variation), % Gage R&R, and % PV (part variation) are calculated by dividing the variation attributable to the category by the total observed variation. Gage acceptability is the ratio of the total gage variation to the specification range. Ten percent is generally accepted as the upper limit for measurement error. Note that only parameter C on Tool 1 has a gage acceptability of less than 10%. The other attributes are much higher, many above 50%.

The Gage R&R study at ATP showed that the test as designed was not precise enough to measure the signal-to-noise ratios effectively given the required specification range.

4.3 Changes Implemented

Based on the data presented above, the yield improvement team agreed to make several immediate changes to the ATP test. First, three test attributes that generated some of the highest CND rates were eliminated altogether. No hard failures had ever been attributed to the three test attributes, and the cost to make the changes was negligible (the tests weren't actually eliminated from the code; rather, the limits were increased to near infinity). Second, the limits on the signal-to-noise ratio tests were doubled.

Two justifications were discussed for the changes, one theoretical and one practical.

Theoretically, the team came to believe that the primary purpose of the ATP test was really to prove that the system could acquire a signal through the antenna and transmit a return signal successfully. The quality of the signal was not as important, as the test environment was significantly different than the field environment (where signal quality is meaningful). The signal-to-noise ratios measure signal quality, so the limits could be expanded without compromising the integrity of the test.

Practically, the limit increases wouldn't change the effectiveness of the test. Figure 9 (page 33) shows a normal curve with mean and variation equal to that of attribute B on tool 2 at ATP. Before the limit changes, a "good" unit with the same mean and variation as other units could fail at ATP by falling into region II. As shown through the Gage

R&R study, a large portion of the variation is due to measurement error. On a subsequent retest, the measured value will vary significantly without any change to the unit's performance, likely falling into region I (and passing). Region II thus represents CND failures.

After the limit changes, the units that fall into region II will pass on the first test, rather than on subsequent retest. The net effect is that the same units will pass with the new test limits as with the old test limits, but fewer tests will be required.

Units that failed for identifiable reason, or non-CND failures, typically fell well outside of the specification limits. They will fail, even with the new test limits.

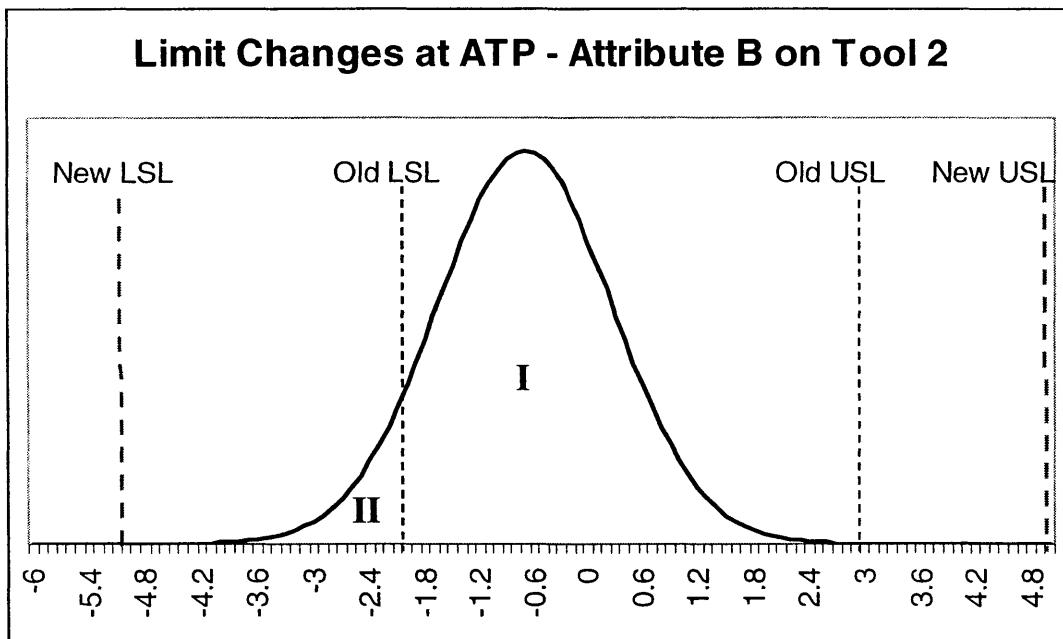


Figure 9 CND Reduction Due to Expanded ATP Limits

4.4 Monitoring Process Performance Over Time – Run Charts and Control Charts

Prior to implementing the ATP test changes, the yield improvement team wanted to be sure that the process would be monitored closely over time to detect sustained shifts in

performance. Historically, process monitoring consisted of failure reports. The team did not feel comfortable relying on yield data alone to monitor the changed process, because it would take a significant shift in the process mean or a dramatic increase in process variability in order for significant numbers of failures to occur.

The ideal solution would have been to develop control charts to monitor the process. I had already calculated process means and variation, so all I needed to do was plot subgroup data on a run chart with control limits at $\pm 3\sigma$.

Unfortunately, and perhaps predictably, it did not turn out to be so simple. The control limits rely on the assumption of normality. I checked the assumption using normal probability plots and found that it did not hold for many of the attributes. The primary reason was that the signal-to-noise ratios were constrained to be integer values by the limited bandwidth of the over-the-air transmission. Creating subgroups of five consecutive tests solved the problem satisfactorily.

Autocorrelation in the data was not so easily solved. Every unit manufactured is tested, so inertial elements in the process lead to correlated data. Traditional Shewhart control charts are very sensitive to the assumption of independence in the underlying dataset. Correlation amongst the data can lead to false alarms. Figure 10 (page 35) shows an autocorrelation diagram for one of the test attributes on test station 2.

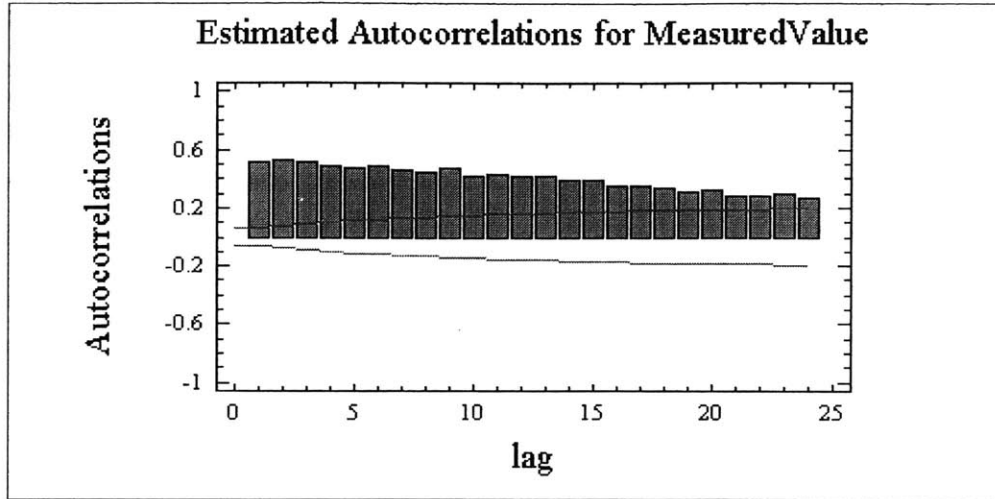


Figure 10 Autocorrelation Chart

Literature suggests several ways to deal with correlated data. One is to model the correlative structure explicitly with a time series model, use that model to remove the autocorrelation, and then apply control charts to the residuals. Montgomery, Johnson, and Gardiner (1990) and Box, Jenkins, and Reinsel (1994) propose a set of models called autoregressive integrated moving average models that can be used to develop control charts for correlated data.

The processes described in literature to deal with correlated data require a significant level of statistical knowledge to prove useful. Run charts of test measurements are intuitive. Operators and engineers alike can relate to the data, because it is in a form they see every day. Run charts of residuals of a time series model or exponentially weighted moving averages are more abstract. They require some understanding of the statistical models used to derive the chart data from the original test results in order to interpret signals in the chart.

Montgomery suggests coupling an Arima chart with a standard run chart of test results. This allows users to visually translate changes in test performance they are familiar with into changes in performance on the statistical control chart. This is a good solution to the

problem, but it still assumes a basic comfort with the method of charting process data and interpreting the results.

Yet QWBS had no experience with the use of run charts to analyze process performance. Presenting the group with a complex set of statistical charts before they were comfortable with the concept in general would have been counterproductive. If the charts weren't easy to interpret, and somehow grounded in the reality they understood, then they wouldn't be used.

So the tool we chose to develop used the old specification limits as "alarm" limits on a run chart of test measurements. Subgroups were used to make the data more normal. The charts allowed the engineers to begin understanding the dynamic nature of the process. It also enabled the team to be warned of potential failures before they began to occur. We created a software routine that checked for subgroup measurements that exceeded the alarm limits (the old specification limits). This gave the group visibility to changes in process performance before yields were impacted.

As the engineers in QWBS begin to feel more comfortable with the use of run charts to monitor process performance, they may find it useful to increase the complexity of the charts by adding the appropriate statistical control limits. This will become especially important if they choose to try to reduce the variability of the ATP test. Until then, the run charts will continue to provide a bridge between the new process data and the knowledge they had developed prior to the change in the specification limits.

4.5 Test Alarm Response Team

The run charts described in the previous section were generated using an Access database application I developed called the Omni SPC Analysis Database. The database, which will be discussed in greater detail in chapter 5, included a set of reports that highlight units that exceeded the alarm limits. The yield improvement team wanted a group of

engineers to respond immediately to these alarm conditions to understand the source of the failures.

The Test Alarm Response team was created to perform this function. The team consisted of the test engineer responsible for the ATP testers, the quality engineer responsible for the Omni test process, the supervisor of the test equipment maintenance and repair group, and myself. My role was to run the database function to check for alarms on a daily basis and to call the team together whenever any alarms occurred. I typically would perform some different analysis before calling the team together to see if I first could determine a potential cause for the alarms.

The team met on two or three different occasions to review alarm conditions. The primary source of alarms came from a group of products that was known to perform right on the edge of the old specification limits due to design issues. The group agreed to ignore alarms for these products unless they deviated significantly from the historical average (as determined by a visual assessment of the run chart).

The team did gain some valuable insight into the process when a set of measurements dropped dramatically on one day. The test measurements for each unit are evaluated in comparison to a reference unit run at the beginning of each shift. The dramatic drop in test measurements was due not to a drop in unit performance, but on one occasion to an increase in the signal-to-noise ratio of the reference unit. This forced the team to reevaluate the purpose and effectiveness of the reference units. Without the alarm response team, that discussion would not have occurred, and the process would not have been as well understood.

The test alarm response team was considered a success because it provided a cross-functional forum for the analysis of operational test data. The Test Engineering and quality groups did not typically work together on anything more than an ad-hoc basis to improve the test process, so the synergy was beneficial.

4.6 Results

The effects of the changes to the ATP test were immediate. First-pass yield improved from 88% to 97%, leading to a projected annual savings of over \$45,000. Figure 11 shows the pareto of failures at ATP in the two months before the test changes. Figure 12 (on the following page) shows the same pareto for the two months following the limit changes.

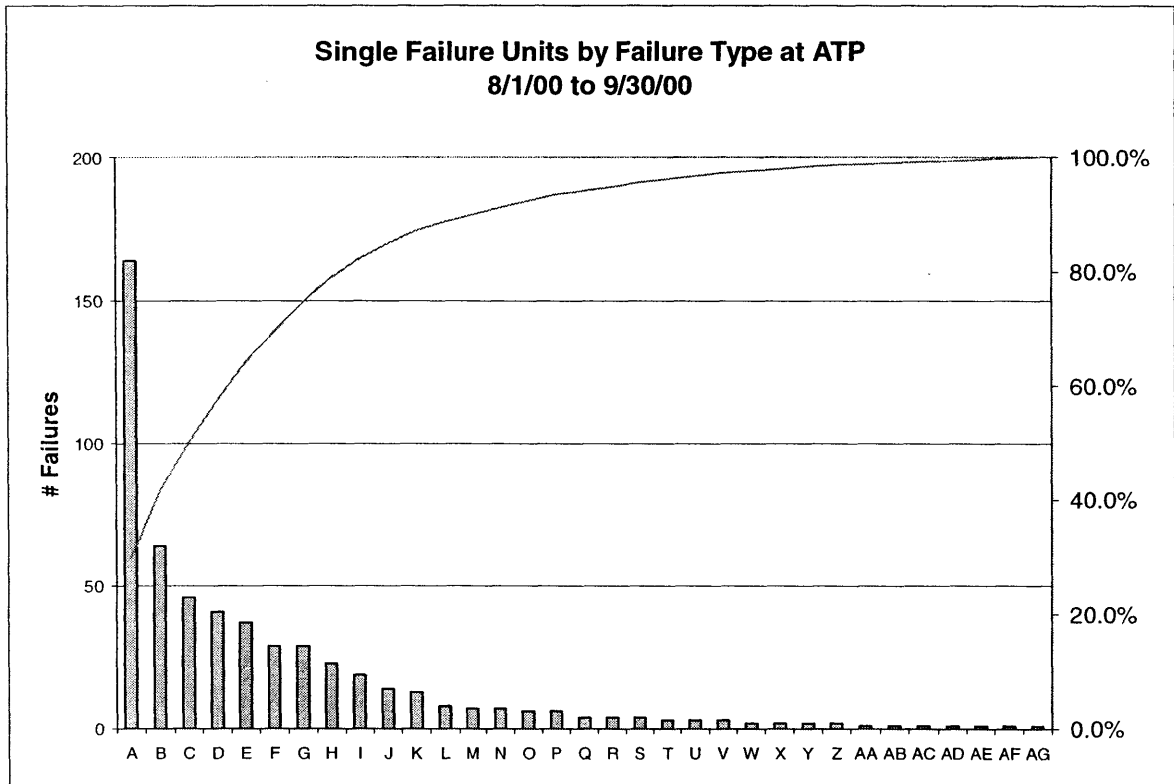


Figure 11 Pre-Change ATP Failure Pareto

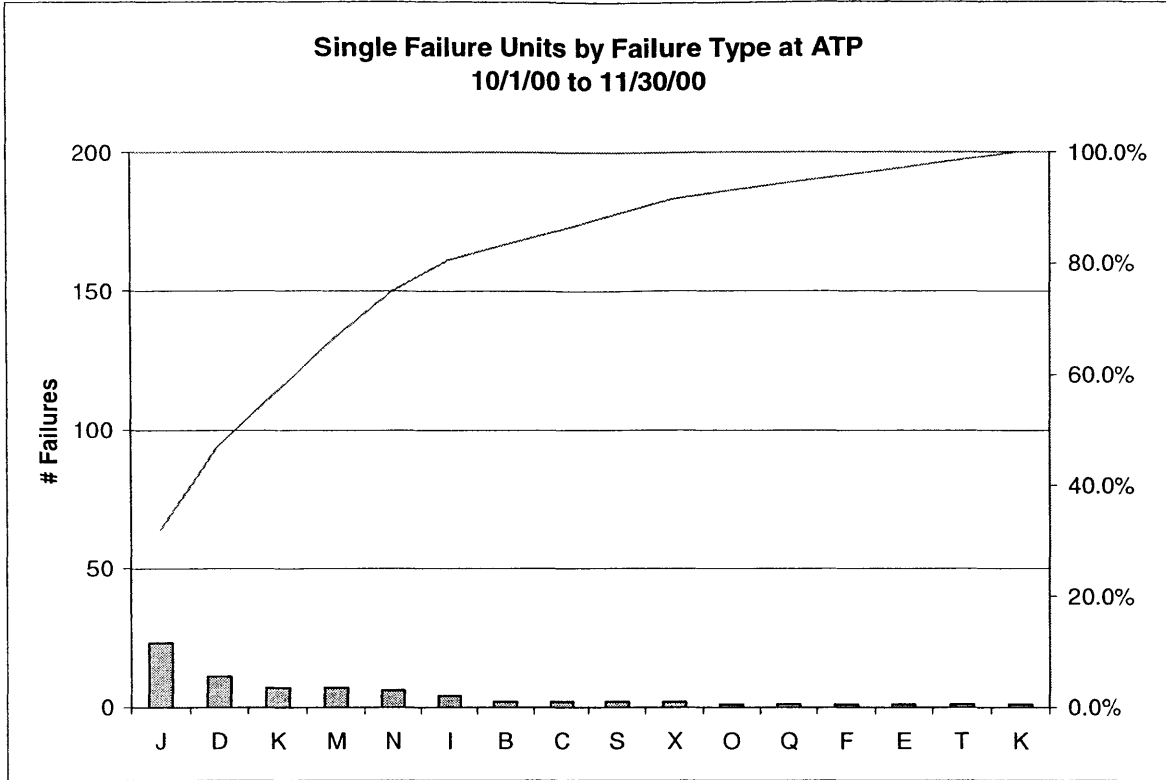


Figure 12 Post-Change ATP Failure Pareto

The total number of failures over a two-month period fell dramatically after the change, from 549 to 72. The number of failure modes also decreased from 33 to 16. By all accounts, the change was a success.

5.0 Software Tools to Support Continuous Process Monitoring

5.1 Initial State of IT Tools

One of the three goals of the internship was to develop an on-line statistical process control tool. The tool would need to fit into the existing IT infrastructure in order to be supported after the completion of the internship. Figure 13 shows a diagram of the software tools supporting the OmniTRACS process. Following is a discussion of each component of the existing system.

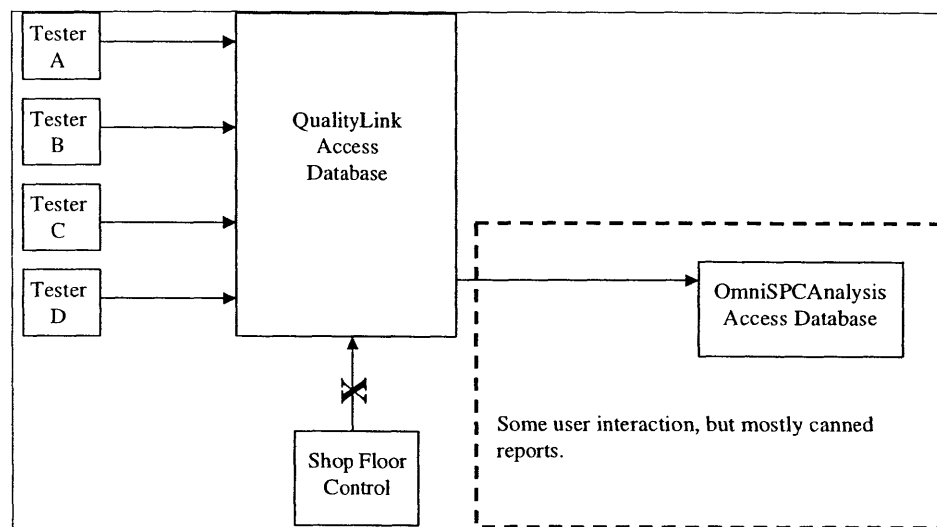


Figure 13 IT Environment Supporting the OmniTRACS Process

5.1.1 Shop Floor Control

Shop Floor Control (SFC) is used to control the flow of materials through the manufacturing line. It was developed in-house, and it utilizes an Oracle database with a Powerbuilder front-end. SFC contains the official as-build configuration that identifies the part number and supplier of each component in a product. It also has a set of quality reports, including yield reports, which are used by the Quality group to monitor test system performance.

As stated in Chapter 2, SFC has no interface to the testers or the QualityLink database. This poses two problems. First, test results must be entered manually into the SFC database by operators on the floor. Parametric test results are not input, only pass/fail attributes with the associated failure code. Dropdown menus of failure codes are available, but users are allowed to enter data not included in the dropdown list. This leads to the potential for discrepancies between the data in QualityLink and SFC. Second, operators must enter the product identifier at each successive test station. Again, no safeguards exist to ensure that the correct part number is input at each test station. This led to cases where a product was identified in QualityLink as coming from supplier A at centerplate functional, but then from supplier B at Vibe.

Ideally, an interface would be developed between QualityLink and SFC. However, the Oracle database on which SFC is based is no longer supported by Oracle. The IT department was evaluating options for upgrading the system, so all development of new functionality was put on hold.

5.1.2 QualityLink

QualityLink is a Microsoft Access database developed by the Test Engineering group to store parametric test results from the OmniTRACS process. Data is transferred to the database from the test equipment at the end of each test (nearly real-time). The front-end of the application provides only a simple query tool that allows data to be extracted from the database and exported to Excel. Consequently, the data in QualityLink is used only on an ad-hoc basis by a limited group of engineers in the Quality group who are familiar with the application.

The design of the database underlying the QualityLink application mirrors the physical test process. A master table identifies all tests performed (date, tool, product tested), and test results are distributed across multiple tables. Some data for like tests are stored together (Vibe and ATP, for example) but each test step basically has one or more tables to store its results. Generic queries to extract test results are difficult to create due to this database design.

5.1.3 Common Test Software (CTS)

The Test Engineering group recognized the limitations of the software controlling the OmniTRACS testers. The code is a mixture of C and C++. The testers are DOS-based and have no room for additional drivers. Maintaining and upgrading the software and hardware is time-consuming and expensive.

CTS was developed to support the next generation product line under development within QWBS. It utilizes a more consistent object-oriented design and it is built on the Windows NT platform. Each tester is controlled by a workstation that could feasibly support additional functionality, such as a web server and/or a local statistical process control application.

Data storage and retrieval were also factored into the CTS design. Data from each tester is stored locally, and then dumped into a data warehouse on a periodic basis. The table structure within the data warehouse is generic, meaning test results from any tester will reside in one of two tables, depending on the type of data. Generic queries and reports could be created easily off of the data warehouse.

5.2 Omni SPC Analysis Database

The Omni SPC Analysis database was developed to support continuous monitoring and improvement of the OmniTRACS product line. The choices of software and system design were constrained by the existing IT infrastructure, the skills of the individuals available to support the system, and the limited development time. Following is a discussion of the design alternatives that were evaluated and a description of the application that eventually was implemented.

5.2.1 Selecting a Development Environment

The goal of the SPC Analysis database was to provide a set of on-line tools to help evaluate the performance of the OmniTRACS manufacturing process. Ultimately, the system would offer the capability to perform real-time statistical process control.

The CTS environment was clearly the ideal place to integrate statistical process control tools. It was the future of test software in QWBS, and it had a robust infrastructure that could support different application design alternatives. Unfortunately, the manufacturing and Test Engineering organizations were not sure if and when CTS would be implemented for the OmniTRACS process. The cost of rewriting the code was significant and the benefit difficult to quantify. Also, virtually no product was being manufactured on the lines supported by CTS (the products were in their infancy and had not gained market acceptance). Thus development efforts in the CTS environment would not provide any short-term benefit to QWBS.

QWBS had multiple data warehousing efforts underway, so another possible alternative was to dump QualityLink data into the data warehouse, and then use a standard OLAP tool like Cognos Impromptu to develop reports and data analysis tools. The engineer within the quality group who was going to support the tool over time had experience developing in the Cognos environment, so this alternative could be supported. But the data warehousing group was over-committed already, and the benefits of adding quality data to the data warehouse were not deemed significant enough to displace an existing project.

The tool would then have to interface with the existing QualityLink database on the back end. Two alternative front-end tools were considered: a Java applet and a Microsoft Access application.

The Java applet would allow access to the application through a web browser on any PC and it would eliminate the need for users to install a program. But the tool would not be supportable initially, as no one in the organization had any experience programming in

the Java environment. The functionality would also be more limited due to the greater complexity of Java development over Access.

The Access application would seamlessly integrate with the QualityLink database, and forms could be developed rapidly. The organization was familiar with Access applications, so the system could be supported relatively easily. Users would be required to run an installation procedure in order to access the data, but the initial user group was expected to be small.

Table 3 summarizes the relative strength of each option across multiple criteria.

Criteria	Java Applet	MS Access
Ease of use	+	+
Supportability (departmental experience with development env.)	-	+
Speed of development	-	+
Ease of installation	+	-

Table 3 Omni SPC Analysis Database Design Alternative Ranking

Ultimately, the ability of the quality group to support a Microsoft Access database and not a Java applet led to the selection of Access as the development environment.

5.2.2 Key Design Features

The OmniSPC Analysis database contains several design features that reflect decisions made during the design phase of the development. The table structure and statistical calculation functions were designed to provide flexibility and enhance the performance of the application. Each design decision involves trade-offs that must be evaluated in the context of the operating environment.

Extensible Table Structure

The overriding philosophy that guided the development of the OmniSPC Analysis database was to provide the user flexibility to perform statistical analysis on every test attribute measured in the Omni test process, without having to write any additional code or understand how to write SQL queries. This required changes to the table structure of the QualityLink database. Data is stored in QualityLink in tables that loosely reflect the physical collection of data in the process. A separate set of tables store the test results for each test step (Centerplate Functional, Vibe, etc.). There is some overlap; Vibe and ATP share a table. Centerplate Functional and Environmental also have data spread across multiple tables.

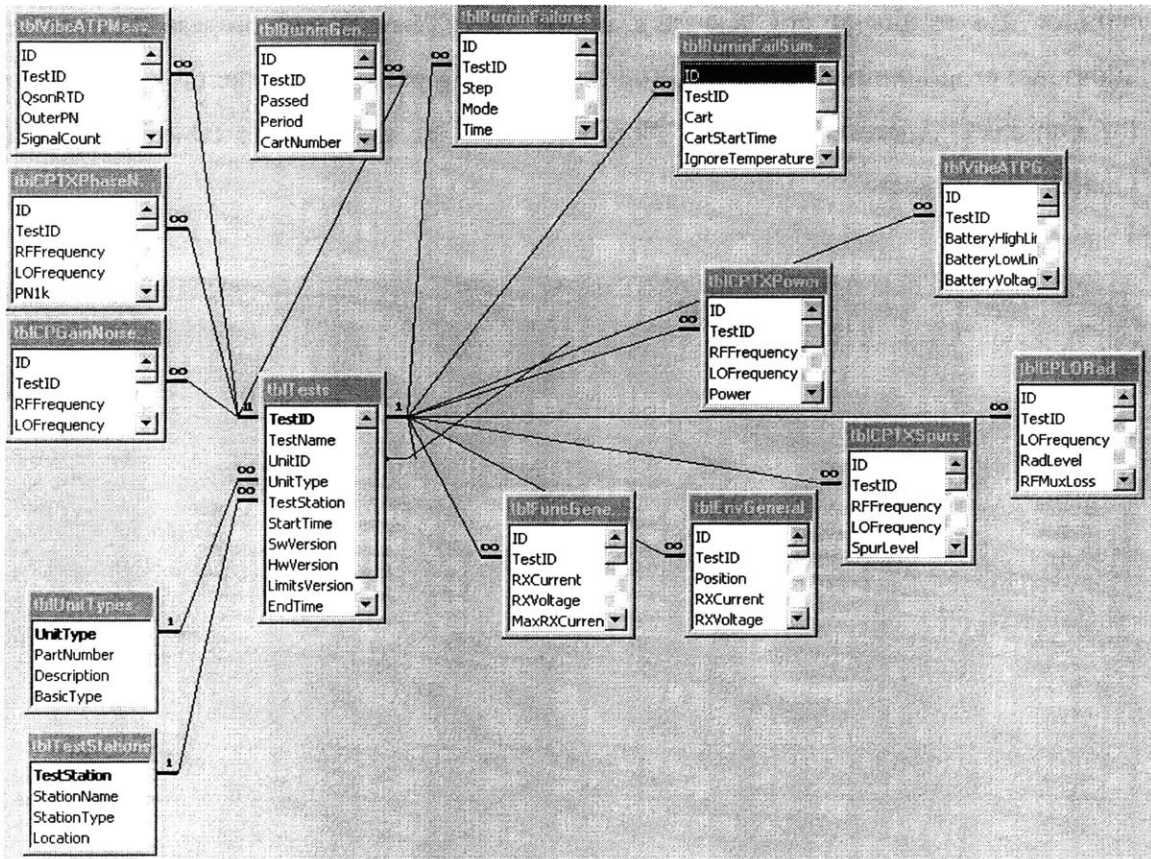


Figure 14 QualityLink Table Structure

I was unable to determine if the QualityLink table structure was consciously designed to support specific needs or if it just evolved to its existing state. Either way, the dispersion

of test result data amongst several tables made it difficult to develop a generic query tool that would easily expand to support future analysis without the need for additional programming.

I solved this problem by creating a new table structure in the OmniSPC Analysis database that aggregates the test results from the different QualityLink tables into one table. A series of associated tables allows the user to identify the test at which a particular test result was measured. The benefit of the single table for all test results is that one query can be created that allows the user to select any subset of data merely by selecting different query parameters (e.g. a date range, a particular test or test tool, etc.). While the database was initially to be used to monitor test results at ATP, it had the ability to monitor test results at any test step in the OmniTRACS test process without any additional programming. Figure 15 (on the following page) shows the table structure of the OmniSPC Analysis database. Note that there are many fewer tables than in the QualityLink database.

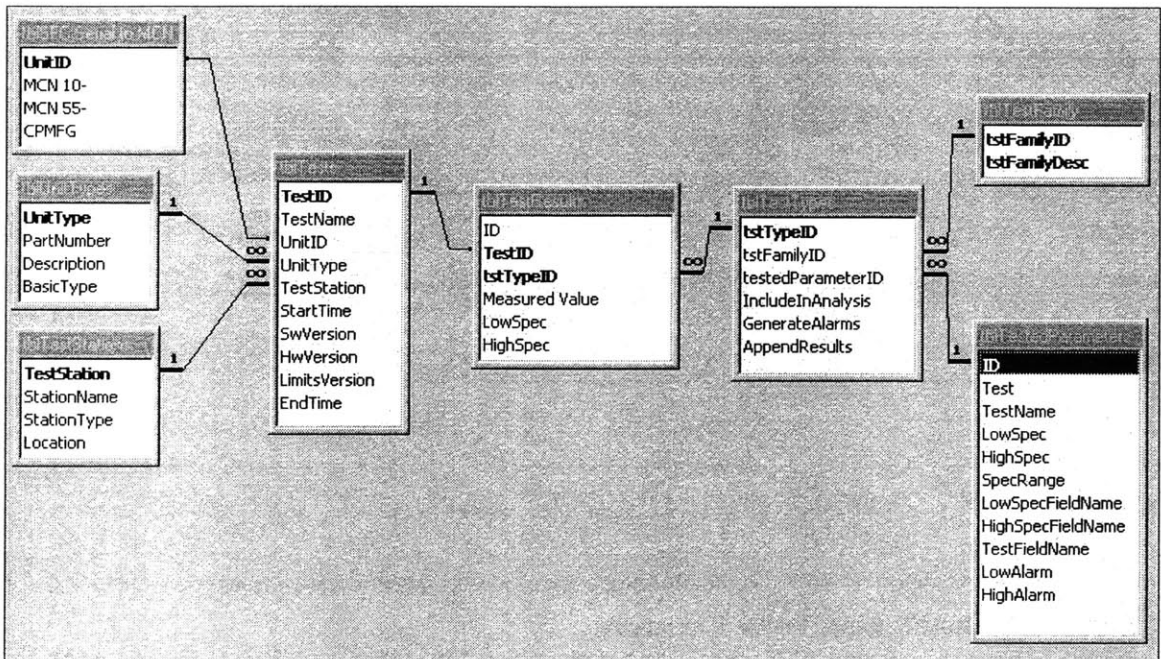


Figure 15 OmniSPC Analysis Table Structure

Changing the table structure had one key drawback. A batch routine is required to insert data into the new tables. The test software automatically logs data into the distributed tables in the QualityLink database on what amounts to a real-time basis. Microsoft Access 97 doesn't contain triggers, so a manual batch update routine is required to copy new test results from the old tables into the new tables. This process could be set up to run on a periodic basis, but initially the user must click a button to run the data upload routine. This means that the OmniSPC Analysis database may not contain the most current information when a user views a run chart or runs a report.

Batch Statistical Calculations

The primary feature provided by the OmniSPC Analysis database is run charting capability for any test attribute on any test station in the Omni test process. The user can select a test parameter, part number, centerplate manufacturer, and test station, and then input a desired date range over which they want to see the run chart of test results. The run chart plots subgroup averages and an additional run chart of subgroup ranges is provided, too. During the design phase, the question was when and where to perform the statistical calculations underlying the data in the charts.

One option was to have the client perform all statistical calculations only when requested. This option reduces the load on the server and may be more efficient, as only the desired calculations are performed. However, performance was unacceptable, especially when a user generated multiple run charts consecutively. The wait between each report generation was too long for the tool to be useful.

Another option was to mimick a data warehousing environment by performing all statistical calculations in the main database and allow users to run reports off of the centralized data. This option reduces the load on the clients and reduces network traffic, as only the desired subset of pre-calculated data is sent over the network to the client. It also reduces flexibility, as all users are limited to the same analysis. If one user wants to view the results in subgroups of 10 and another in subgroups of five, they wouldn't be able to do so simultaneously.

The solution implemented combines elements of both options to improve performance and maintain flexibility. Statistical calculations are performed on the client's system, but all calculations are batched and performed at once. The user can select which test parameters and test stations to include in an analysis, but when the statistical calculations are performed, they are performed for all test parameters, test stations, part numbers, and centerplate manufacturers at once. This eliminates the need for any statistical calculations when the user selects a run chart for viewing, enabling the charts to open virtually instantaneously.

5.2.3 Resulting Application

The resulting OmniSPC Analysis application provides a platform for QWBS to begin monitoring and improving process performance over time through the use of statistical quality control tools. Quality and test engineers now can quickly see trends in test data and drill down into the underlying test results to determine potential causes of shifts in results.

Figure 16 and Figure 17 are examples of run charts generated by the OmniSPC Analysis database. Figure 16 shows the performance of a nominal minus reference value of a test attribute on a test station at ATP. Note that the test results fall below the lower alarm limit for a period of time. And Figure 17 shows the same data set, only nominal test results are plotted instead of nominal minus reference. This chart is useful because it shows that the nominal test results fell by only half of a dB, which is not enough to account for the nearly 3 dB drop in the nominal minus reference values seen in Figure 16. An increase in the reference unit's measured value led to the apparent drop in system performance, not a decrease in unit performance. This information is invaluable to the test and quality engineers as they seek to improve the performance of the ATP test.

Test Level: MCT ATP
Parameter:
MCN:
Centerplate Mfg:
Test Station:

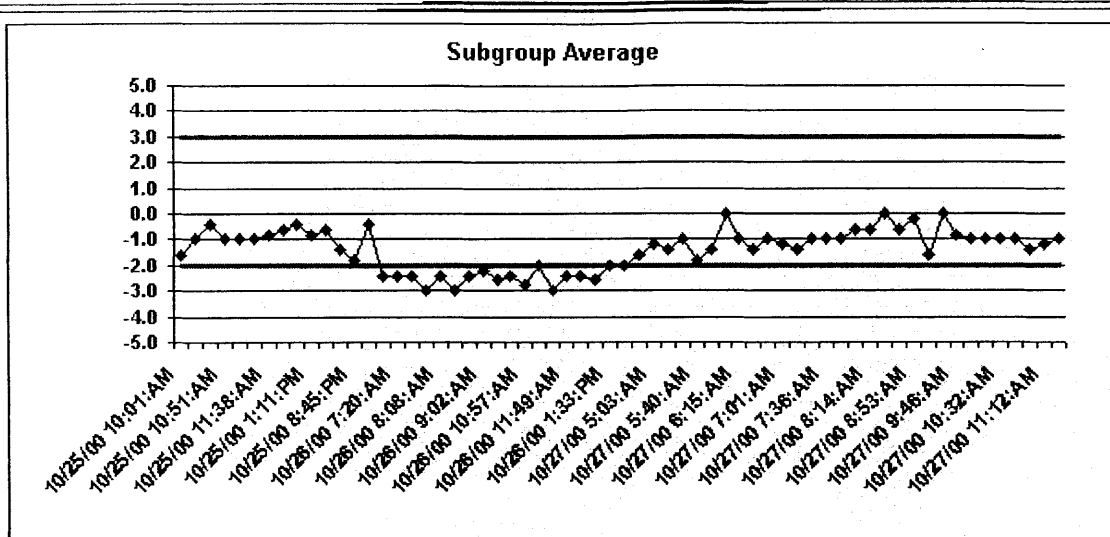


Figure 16 Subgroup Average Run Chart Example

Test Level: MCT ATP
 Parameter:
 MCN:
 Centerplate Mfg:
 Test Station:

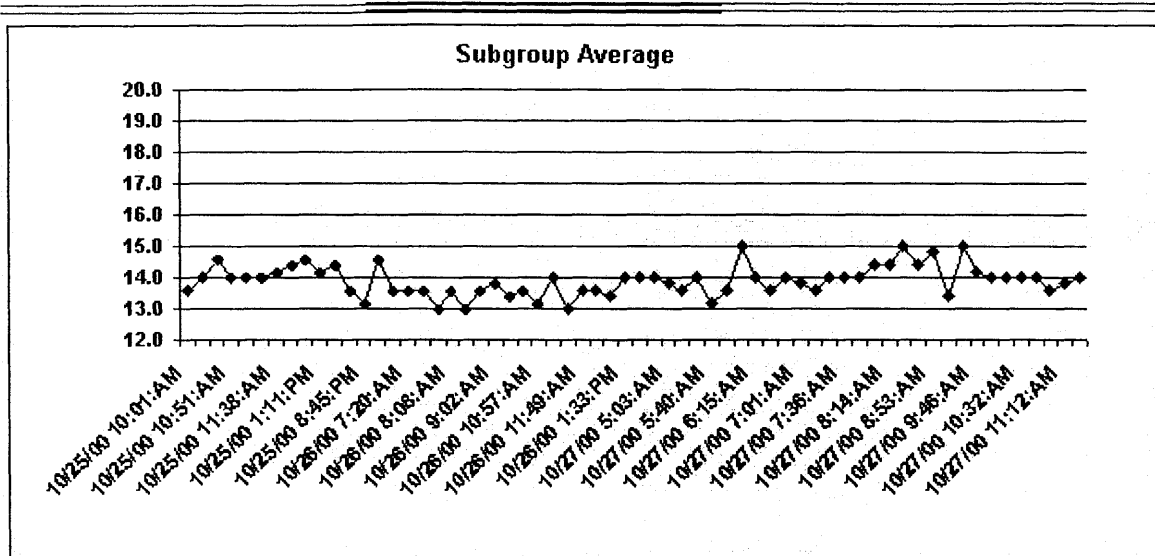


Figure 17 Nominal Subgroup Average Run Chart Example

5.3 Recommended IT Vision

The OmniSPC Analysis database is an effective tool to help QWBS begin using statistical quality control to understand and improve the performance of the OmniTRACS test process. However, it is not a robust, enterprise application. Nor is it the most efficient tool to provide the functionality it delivers. If QWBS finds the tool useful and wants to expand upon the capabilities offered by the OmniSPC Analysis database (by developing real-time SPC, for example), then it needs to integrate the capabilities into its enterprise IT environment.

Figure 18 (page 51) outlines a vision for the IT environment that would support both real-time statistical process control and on-line analytical processing of test data. In this scenario, each tester runs a local application that monitors the state of the tool. Ideally, each tester would run a web server, enabling engineers to monitor tool performance remotely over the web. Data from each tester is uploaded into a data warehouse

environment, where it is formatted for efficient analysis and reporting. The data warehouse would include an interface with the Shop Floor Control system to obtain as-built configuration data to address the problems discussed in section 5.1.1. Canned reports and analysis could be developed with Cognos reporting tools in use in other areas of the organization. If more flexibility is desired, a separate application could be developed that pulls data from the data warehouse, as well.

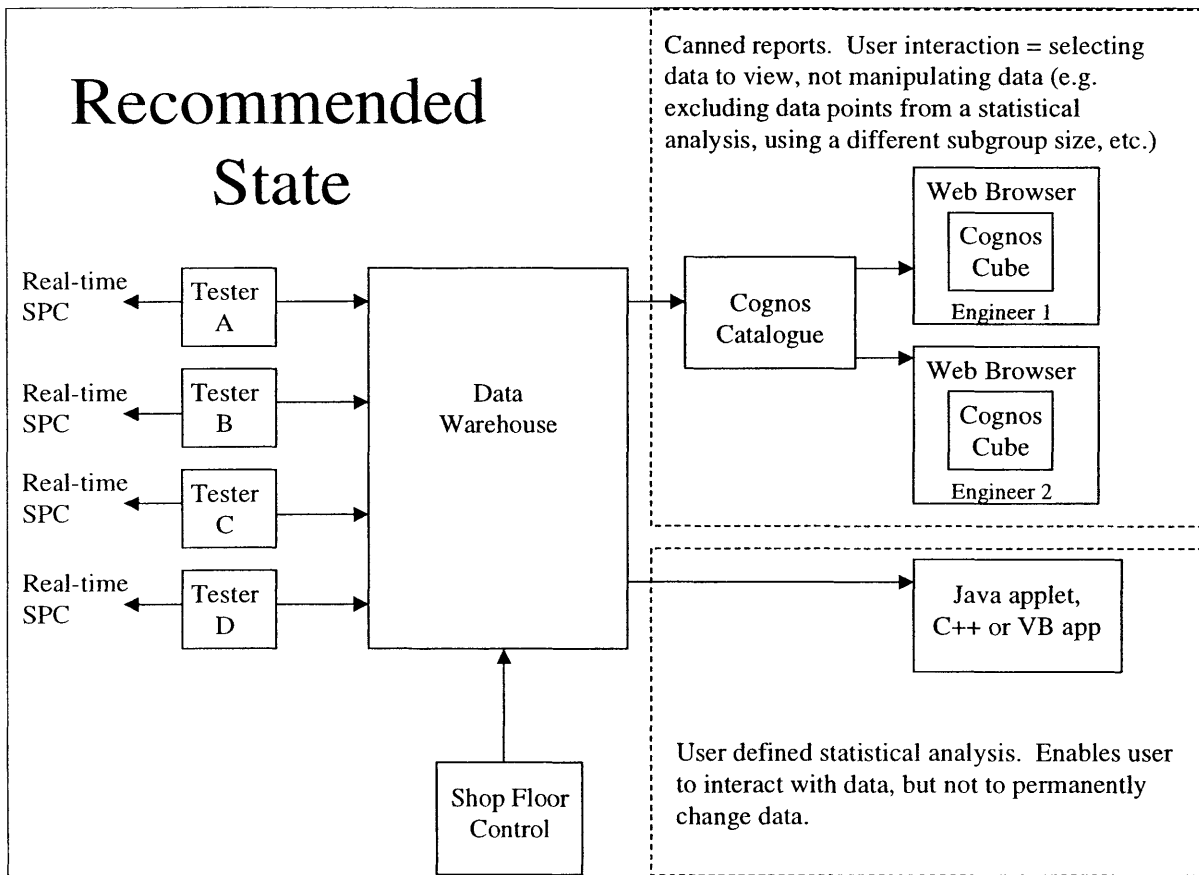


Figure 18 Recommended IT Environment

6.0 Organizational Observations

Ideally, the internship process consists of more than just performing a specific task or analysis for a company. The goal is to facilitate a sustainable improvement in the organization. Analysis of the organizational setting and the context in which the internship/project is operating is essential to achieve this goal. This chapter uses several tools to analyze the QWBS organization. Section 6.1 uses the three lenses approach developed by Ancona, Kochan, Scully, Can Maanen, and Westney to evaluate the project from the strategic design, political, and cultural perspectives. Section 6.2 discusses how the change process was managed during the internship. And section 6.3 evaluates the overall effectiveness of the internship as an organizational change initiative and offers some recommendations for future efforts.

6.1 Three Lenses Analysis

The three lenses provide a useful framework for analyzing the internal forces that affected the effort to improve QWBS's manufacturing test processes. Without explicitly using the 3 Lenses framework, the organization had already recognized some of the political issues that the framework reveals before the internship began, and they instituted some changes in an attempt to fix those issues. However, the analysis provides some additional insight into the factors working against successful implementation of process improvements.

6.1.1 Project Setting

Before the internship began a yield improvement team was created that had four goals:

- Improve yields (95% First-pass Yield at each test step)
- Lower product cycle time
- Improve quality
- Understand CND failures

Team membership included the head of the Test Engineering department (the developers of the test hardware and software), the head of the Quality department (part of

manufacturing), and representatives from engineering (the product designers) and operations. The team made little progress. Team members didn't have or make the time to gather the data necessary to make informed decisions. Political clashes between the head of the Test Engineering group and the manufacturing organization interfered with meaningful discussion.

The internship was proposed to help the team achieve its goals. The manufacturing group recognized that it lacked a dedicated resource to collect and analyze process data, and an intern would be able to provide the singular focus the project needed to make progress. Also, the organization recognized its inexperience with the use of statistics to evaluate process performance. The hope was for an intern to bring those skills into the team to be used both to help improve the test process and to teach the organization how to use statistics more effectively to improve the manufacturing operations.

As the intern, I reported to the manager of the Quality group and I participated on the existing yield improvement team. Most of the analysis I was to perform could be done so individually, but members of the quality and Test Engineering groups and operators on the factory floor were all available to provide assistance when needed.

6.1.2 Strategic Design Lens

Five different groups were represented in the yield improvement team. The formal organizational design is represented in Figure 19.

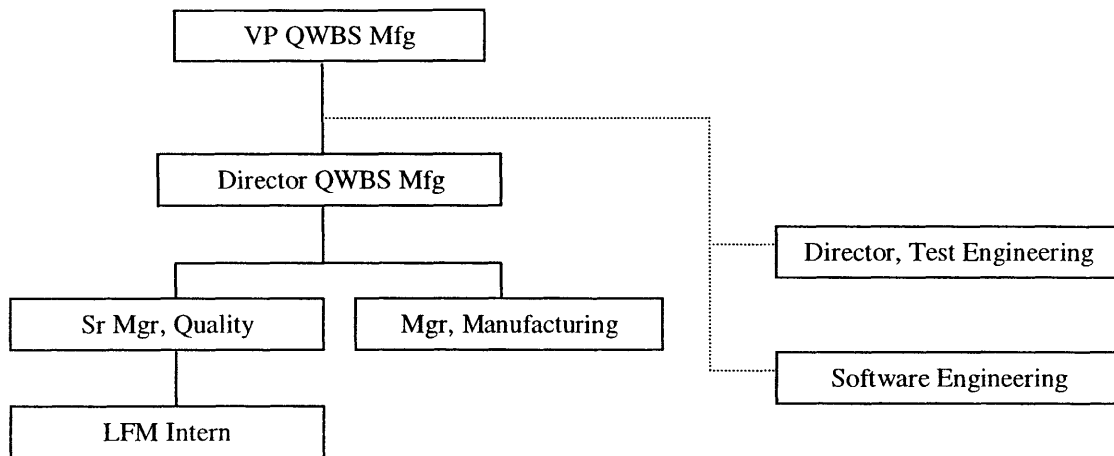


Figure 19 QWBS Organizational Design

The key elements of interest in the organizational structure are the shared reporting structure of the Quality and manufacturing groups, and the matrixed relationship of the engineering groups to QWBS. This is important because the degree of alignment of group strategies was related to the reporting structure.

The manager of the Quality group believed that the test process was inefficient and that it could be improved by eliminating tests without reducing the quality of the end product. His strategy was to work through the yield improvement team to convince the engineering groups (primarily the Test Engineering group) to eliminate test steps from the process. He wanted to make wholesale changes at once, as he thought that historical test result and field return data supported his belief that the product quality wouldn't be adversely affected. My internship was key to this strategy; I was to collect the data and perform the statistical analysis that would convince the group to make changes.

The manufacturing group was closely aligned with the Quality group. Its primary strategy was to reduce manufacturing costs, so it supported the Quality group in its efforts to eliminate test steps. Its key goal was to eliminate the Burn-In test; the two burn-in tools consume a lot of power and they account for a significant portion of the test time, and they take up a lot of floor space.

The Test Engineering group agreed with the strategy to improve the efficiency and effectiveness of the test process, only it wanted to be more deliberate with the change process. A new director came into the position just before my arrival, and he wanted to change the focus of his organization. Historically, the Test Engineering group owned the test process. It developed the test software, selected and or built the test hardware, and acted as the “defenders of product quality” (which translated into “don’t change the test process because it works”). The new direction with the new director was to focus on the development of robust test systems (hardware and software), but to let the quality group choose which tests it wanted to perform on its product.

To support this strategy, the Test Engineering manager wanted to lay out the entire test process and look for overlaps in test functionality. He was extremely interested in my project, as he recognized the value of statistical analysis, but his organization didn’t have any expertise in that area. He hoped that I would be able to develop some tools that would enable his group to utilize statistical quality control to improve the repeatability and reliability of the test processes they developed.

The strategies of the other engineering groups (both hardware and software) involved in the project were somewhat in conflict with the efforts of the yield improvement team. The primary goal of these groups was to ensure that the changes to the test systems proposed by the team wouldn’t inhibit their ability to test the effects of product changes under design. This goal reflects these groups’ view that one role of the manufacturing line was to be a test ground for the engineering organization. They were comfortable with the existing test process, because they understood its capabilities. Convincing the

engineers in these groups to make changes in the process would require a different set of criteria than that required for the rest of the team.

Since the different stakeholders involved in the project didn't report to a single manager with decision-making authority, the yield improvement team had been created to facilitate interaction amongst the different groups. Team membership included the heads of each group, so the group had sufficient decision-making authority. Resources could also be committed, so no additional structure was required to obtain approval for implementation efforts.

The distribution of skills and knowledge amongst the various organizations made it necessary for me to work closely with both the Quality group and the Test Engineering group throughout the project. The Quality group continuously analyzed test results, so it understood which tests were problematic. The Test Engineering group didn't spend much time looking at process or product performance, but it knew the tasks performed at each test did, and how they are performed. Additionally, the group had control over the data collection systems for test results. Gaining an understanding of how the tests worked was essential to the development of meaningful statistical tests. Accessing the source data allowed me to both run the statistical tests and create an application to automate data analysis in the future.

Based on my recommendations, the yield improvement team agreed to eliminate some tests and to expand specification limits on some others. The Test Engineering group was concerned that expanding the test limits would allow the process to drift off target without warning, so I developed an application that checked test results against the older specification limits and generated alarms whenever the test results exceeded those limits. An alarm response team was created to respond to these conditions as they occurred. The team was unique because it included staff engineers from the Quality group, the Test Engineering group, and the manufacturing operations group. Bringing representatives from all three groups together allowed the team to better diagnose the cause of an alarm condition and to develop solutions. The test alarm team was the first cross-functional

implementation team of its kind in QWBS; it created a learning environment where product and process knowledge were combined to improve the manufacturing process. It was successful because the formation of the team was a consensus decision amongst the various members of the yield improvement team.

At the end of the internship I recommended that each test step be assigned to a specific engineer who would have total responsibility for the tool's performance, including yield and maintenance. The existing organizational structure distributes ownership of the tester performance across three groups, which makes accountability for the tester performance more difficult to assign. Intel Corp., for example, successfully utilizes the concept of module owners in its factories to ensure each tool has a resource dedicated to maintaining and continuously improving its performance, and I believe that a similar focus would facilitate process improvement efforts within QWBS.

6.1.3 Political Lens

While the structure of QWBS and its relationships to the engineering groups posed some challenges to implementing changes to the test process, politics played the biggest role in determining the success of the project. Multiple stakeholders participated on the yield improvement team, each from organizations with different strategies and each with different interests and sources of power. By understanding the different stakeholder needs, I was able to forge relationships that enabled me to transcend the politics that had hindered change in the past.

Table 4 summarizes the interests of each stakeholder involved in the project.

Stakeholder	Interest in project	Gain/Lose
Quality Mgr	<ul style="list-style-type: none"> • Improve process yields • Gain more control over design of the product testing process • Prove product can be made cheaply in San Diego (so not all products will get outsourced) • Improve understanding of statistical performance of the process 	<ul style="list-style-type: none"> + Status as experts in evaluation of process performance + Power for quality group + Executive attention for increasing yields and reducing mfg cost - Lose status if process changes lead to quality excursion that affects customers
Test Engineering Manager	<ul style="list-style-type: none"> • Improve the test process • Learn statistical tools that will help the group design better tests in the future • Provide support to key customer (mfg) to help meet cost targets • Develop better relationship with quality group. Be seen as team player 	<ul style="list-style-type: none"> + Perception as responsive to customer needs + Perception of the efficiency of the test process - Job at worst, or status within engineering group, if test changes lead to quality excursion
Manufacturing Operations	<ul style="list-style-type: none"> • Reduce labor required to support testing. • Want to gain floor space and reduce energy consumption by eliminating burn-in testers • Reduce process costs by improving yields, which makes mfg in San Diego more competitive 	<ul style="list-style-type: none"> + More efficient manufacturing operation - Potential to lose jobs if mfg eventually outsourced to Mexico to save costs
Product Engineering	<ul style="list-style-type: none"> • Keep track of mfg process changes that could affect their ability to test effects of product changes (e.g. ensure that we don't get rid of a test they need) 	<ul style="list-style-type: none"> + Improve synergy with mfg and Test Engineering - Capability to test certain parameters
David Knudsen	<ul style="list-style-type: none"> • Make a meaningful contribution during internship • Show positive NPV for internship • Learn more about Statistical Quality Control 	<ul style="list-style-type: none"> + Respect of team members + Status within LFM (esp. staff) based on perceived quality of internship
LFM (program + Advisors)	<ul style="list-style-type: none"> • Want intern to have a quality experience with the opportunity to effect change in an organization • Show ROI to company for student's efforts • Improve working relationship with Qualcomm 	<ul style="list-style-type: none"> + Future internship opportunities + Future program support
Advisors	<ul style="list-style-type: none"> • Want to work on interesting problem with academic implications • Internship should have sufficient engineering content 	<ul style="list-style-type: none"> + Potential learning opportunity

Table 4 Stakeholder Interests

Figure 20 displays a map of the different stakeholders.

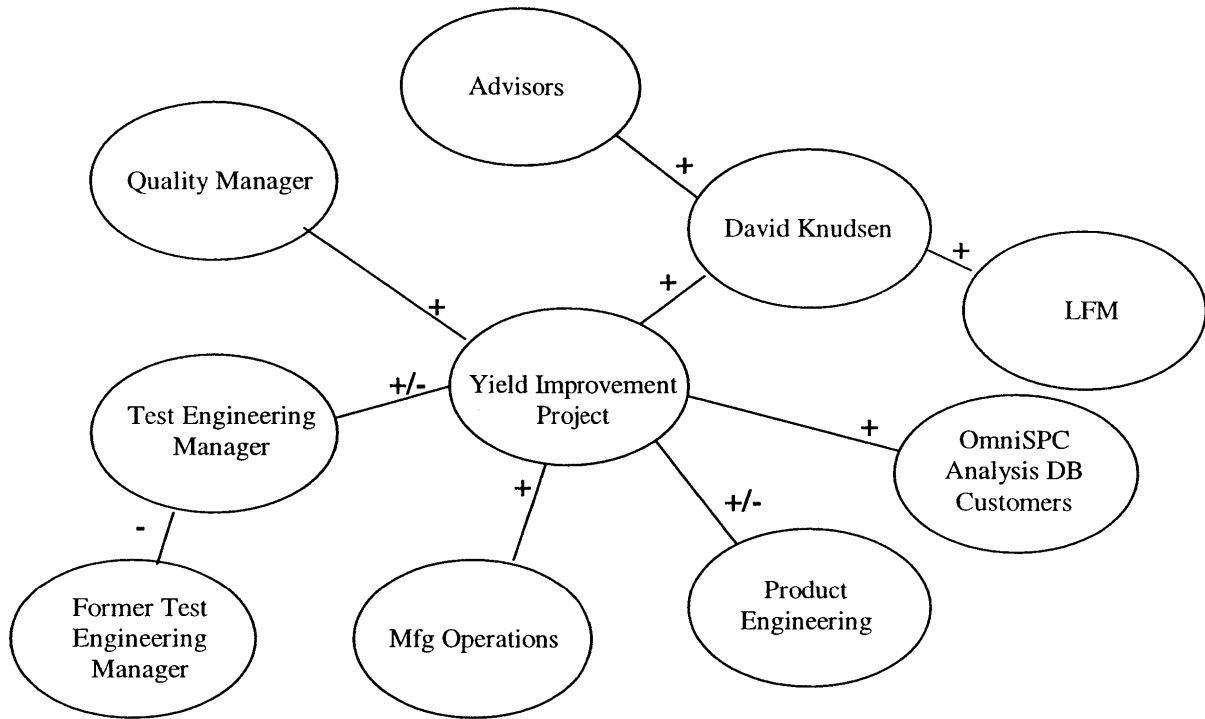


Figure 20 Stakeholder Diagram

In general, the interests of each stakeholder were fairly well aligned. This was due primarily to a change that had been made in the Test Engineering management. Up until the time the internship started, the same Test Engineering manager had been running the group for years. He believed that the test suite that had been developed worked well, as evidenced by QWBS's reputation for high-quality products. He resisted suggestions on how to improve the process, even when they were based on data. Some members of the organization believed that he didn't want to give up the power that he had developed in his position.

The former manager of the group was replaced by a member of the Test Engineering organization with the expressed goal of improving teamwork between Test Engineering and manufacturing. Thus the new manager's interests were aligned with those of manufacturing at a high level.

However, the new Test Engineering manager recognized that he was ultimately responsible to the engineering management, not manufacturing, and any foul-ups caused by changes to the test process could mean his job. Thus he was more cautious, wanting to create a convincing case based on good data and sound analysis before instituting change.

As stated previously, the product engineering groups represented on the project were primarily concerned about their ability to test changes to the product they designed. They understood the capabilities of the existing test process, and they were generally wary of change.

While the interests of each stakeholder involved in the project were reasonably aligned, the distribution of power amongst the stakeholders was very unequal. The Test Engineering group historically had controlled the test process. They defined the content of the tests, the tools used to perform the tests, and they established their own list of priorities for maintaining and improving the process. Manufacturing had little input. They made suggestions on where to focus resources, but had little influence over the Test Engineering group.

The Test Engineering group also established the specification limits of the tests, which meant that it basically controlled the determination of what product could be shipped to customers. The Quality group had some strong feelings about the validity of some of the test limits, but they had been unsuccessful in getting them changed.

If the project was successful, the manufacturing (and Quality) groups stood to gain power from the Test Engineering organization. They would wrest some control over the establishment of test limits, and they would gain influence over the allocation of Test Engineering resources.

The real power within the organization seemed to reside in the product engineering group. Qualcomm was founded by engineers focused on technology, not manufacturing,

and ultimate power remained in the hands of the developers of technology. My project wasn't going to change that dynamic. The product engineers participating on the team could derail the process if it affected them adversely, so it was important to ensure they understood the nature of any proposed changes and the justification for making the changes.

The biggest challenge facing the yield improvement team was overcoming past norms of decision making. Historically, the Quality group would present data to the team summarizing the frequency of each type of test failure, trying to justify the elimination or change to a test. The team would then either argue about the validity or interpretation of the data. The arguments were typically based on personal beliefs that weren't stated expressly. These conflicts were "resolved" by inaction and frustration and no changes were made. Fortunately, the management change within the Test Engineering organization eliminated a key source of these personal differences, enabling the group to better focus on collecting and analyzing data to make informed decisions.

6.1.4 Cultural Lens

The yield improvement project had symbolic meaning on several different levels. An unspoken concern in the group was that all manufacturing would eventually be outsourced to lower cost contract manufacturers in Mexico. The drive to improve yields represented on some level an effort to save manufacturing in San Diego. The project also symbolized the effort to improve working relations between the Test Engineering and quality groups. Finally, the internship reflected the desire to incorporate more rigorous statistical analysis tools into the manufacturing process.

The project focused on the collection and presentation of unbiased, statistical data that helped explain *why* products were failing, not just stating that they were. This provided a different focus on data than was the norm. I also tried to follow a more rigorous process for problem solving – identifying the issue, proposing an experiment to collect data, developing evaluation/decision criteria, collecting and analyzing data, presenting results,

and making a decision. This challenged the team to work outside of its typical methods of making decisions. Hopefully, the example of a more rigorous approach to problem solving and decision making will influence the team processes used in the future.

As an outsider, I was also unaware of and/or unconcerned about some of the cultural symbols that restrained some other members of the organization. Badge number played a large role in the amount of influence wielded by team members. For instance, one typically outspoken team member was hesitant to defend his ideas when questioned by a senior member of the product engineering organization. Unconstrained by a fear of badge number, I confidently justified my use of statistics in a particular experiment we had designed. As it turned out, respect for technical competence won out over any political issues, and my behavior was positively reinforced. This dynamic may have been different had I been looking for a long-term position within the organization, but my status as an employee of another company enabled me to avoid any socialization that may have occurred otherwise.

Formal communication of my project consisted of an email introduction saying I was working on a project to help improve yields. The yield improvement goals were reviewed in the Quality team meeting once or twice during the six months I was there, but basically the project visibility was limited to those participating on the yield improvement team and to those who were assigned tasks by the team. Updates were provided on a monthly basis to senior staff by the quality manager, but I was not invited to the meeting where this took place, so I don't know how much emphasis senior management placed on weekly progress toward the team goals.

My role on the project was communicated primarily in the introductory email, which played on the fact that I was an outside "expert" from MIT. Since technical skills are valued in the organization, the MIT brand name gave me instant credibility, both within the engineering ranks and down on the factory floor.

As my skills became evident to the organization, some engineers saw my presence as an opportunity to get their own projects moving (utilizing my statistical knowledge to perform some experimental data analysis, for example). I became a technical resource to complete tasks they either didn't know how to do or didn't have the time to do. Operators on the floor saw me as a person to tell their problems too, expecting that I had the power somehow to fix them. Irrespective of how I was perceived by different members of the organization, I was uniformly treated as a colleague and employee, not as an outsider. I think that is reflective of the open, congenial culture of Qualcomm (and perhaps San Diego, more generally).

6.1.5 Putting the 3 Lenses Together

Each lens on its own provides useful insight into the organization. However, when the three are used simultaneously, you begin to notice causal relationships that can help guide change efforts. The political lens tells me that the engineering organizations have a lot of power, and the cultural lens reveals that low badge numbers, primarily belonging to the founding engineers, carry prestige and respect. The strategic design lens tells me that the Quality group should have the authority to make changes to the test process, but the political lens shows that it didn't have the influence to do so.

These observations are useful tools in planning the change process. They help identify the key players and how they can be influenced most effectively. They also point out potential potholes that should be avoided.

While general lessons can be drawn from the process of the Three Lenses analysis of the QWBS organization, the findings are specific to the organization. Symbols of power in an organization (low badge number, in this case) are different across companies. The key lesson is to recognize the value of understanding the organization in which you are trying to implement change and to use that knowledge to achieve results.

6.2 Managing the Change Process

The yield improvement process was not embedded in a larger organizational change initiative. The Quality group was working to implement HALT (highly accelerated life testing) and HASA (highly accelerated stress auditing), but its efforts focused on the newer products under development, not the OmniTRACS product. The project related to the 2 x 4 plan described in the introduction (double revenue and double profitability in four years) in that future cost reductions would need to come from improved manufacturing efficiency. The 2 x 4 initiative was not publicized visibly, though; the average employee would likely not even know of its existence.

The change model our project implicitly embraced was bottoms-up, incremental, and continuous. We were forging a new relationship between Test Engineering and Quality that would help facilitate future process improvements. Our plan was to make changes to the test process one step at a time, focusing on the end of the process first. The incremental process would allow the team to learn from each change, allowing it to improve the change process and minimize the risk to product quality. The statistical software tools I developed would allow the team to continue evaluating the statistical state of the process and make additional improvements. The change process was emergent in that we weren't really sure what skills and/or structures would be required to support the changes until we had determined the nature of the changes.

6.2.1 Kotter's Eight Steps

Table 5 summarizes the change process in terms of Kotter's eight steps.

Step	Action taken
1. Establishing a sense of urgency.	<ul style="list-style-type: none"> • 2 x 4 plan necessitated cost reductions in the manufacturing operations. Process efficiency improvements required to meet the goal. • Market demand decreasing and competition increasing. QWBS beginning to outsource mfg of newer products, and headcount had been reduced in San Diego facility, so need to improve efficiency to save jobs.
2. Forming a powerful guiding coalition.	<ul style="list-style-type: none"> • Yield improvement team created with head of Test Engineering, head of quality, head of mfg operations, and primary designer of the OmnitTracs product.
3. Creating a vision.	<ul style="list-style-type: none"> • Yield improvement team established a goal of 95% first-pass yield at each test station. ◆ I used statistical analysis of process data at the last test step to show the potential yield improvements and cost savings of eliminating some tests and increasing spec limits on others at the final test step.
4. Communicating the vision.	<ul style="list-style-type: none"> • Quality manager presented yield targets to senior management in mfg, Test Engineering, and product engineering. Communication to shop floor done primarily as an FYI, since the process changes primarily involved software changes, not operational changes. ◆ Presented ATP change plan and potential cost savings to yield improvement team.
5. Empowering others to act on the vision.	<ul style="list-style-type: none"> • Eliminated primary barrier to change by replacing the manager of the Test Engineering organization. • Funded the internship to bring in a dedicated resource to focus on the project.
6. Planning for and creating short-term wins.	<ul style="list-style-type: none"> ◆ Yield improvement team started with easy-to-implement changes to the last test step (ATP) that immediately improved ATP yields from 88% to 98%. ◆ Developed database application that enabled quality engineers and test engineers to monitor process performance graphically. The tool enabled the implementation of the ATP changes.
7. Consolidate Improvements and Produce More Change	
8. Institutionalize the New Approaches	

Table 5 Kotter's Eight Steps to Transforming the Organization

Table 5 includes actions taken on the part of the QWBS organization to facilitate the yield improvement efforts (round bullets), and actions taken on my behalf as a part of my internship (diamond bullets).

By the end of my internship the project reached a stage where we had achieved a short-term win with the ATP changes, but did not progress to the next step of consolidating the improvements. My final presentation to the QWBS management recommended that some engineers be dedicated to process improvement efforts and that all of the staff engineers be offered training in statistical quality control tools, but no action was taken on those recommended actions before the conclusion of the internship. Had I been a permanent member of the organization, I would have continued to advocate for the institutionalization of SPC practices to consolidate the changes we had made already.

6.2.2 The Yield Improvement Team – Internal Process Assessment

The internal processes used by the yield improvement team, and at QWBS in general, were inadequate. Team meetings generally consisted of a group of engineers arriving 10 minutes late, grabbing their requisite drink provided by the meeting coordinator, and then updating each other on any progress made since the previous meeting. Agendas were few and far between. Discussions tended to wander off topic, and team members seldom stepped in to bring everyone back on track. Quiet team members were rarely engaged in discussion. Decisions were rarely documented.

Early in my internship I brought up this observation with my supervisor, who was leading the yield improvement team. He agreed with my assessment and proceeded to show me the work the team had done when it was first formed – team charter, roles and responsibilities, expectations, metrics, and success criteria. He had clearly taken a class on high-performing teams, but he had not translated the learnings into his daily management techniques.

I suggested a template for documenting decisions made, and even presented it to the team at one meeting, but the response was underwhelming. It would have been inappropriate

for me to try too hard to force change on the team. Norms had been established, and my supervisor was the team lead. Instead, I coached team members whenever opportunities presented themselves.

I'm convinced that one of the primary reasons for the team's inability to accomplish its goals prior to the internship was due to the lack of team processes. A "team" was never truly created. Decisions were not made, because a process to make them was never established. Strong team processes may have been able to overcome the political and organizational barriers to implementing change. Weak team processes amplified the barriers, making change nearly impossible.

In retrospect, I should have spent more time trying to better implement team processes characteristic of high performing teams. This would have contributed more to organizational learning than to a specific technical analysis. My lack of positional authority made it difficult, but I could have pushed harder on team processes like agendas, decision tracking, decision criteria, and performance measures.

6.3 Evaluation and Recommendations

Recall the yield improvement team's four primary goals:

- Improve yields (95% First-pass Yield at each test step)
- Lower product cycle time
- Improve quality
- Understand CND failures

As stated in Chapter 4, first-pass yields at the final test step had improved from 88% to 97% by the end of the internship. The average test time per unit had fallen from ~10 minutes to ~6 minutes at ATP. Product quality remained unchanged, subject to inspection of future data on field returns. And the team could explain why CND's occurred at ATP. The changes resulted in anticipated annual savings of over \$45,000, and the OmniSPC database I developed would help tackle the next round of improvements.

Excitement with the results was apparent at all levels of the organization. The VP of Manufacturing (the internship sponsor) was appreciative of my contributions, but more importantly, she wanted to know who was assigned to carry on with the data analysis in my absence. She valued the results enough to focus on sustaining the momentum the team had gathered.

Unfortunately, I don't believe that the learning diffused sufficiently throughout the organization to be sustained without the addition of resources dedicated to process improvement. The engineers with the skills to lead process improvement efforts are over-committed just fighting fires, and the incentive system of the organization rewards that behavior. Some eyes had been opened, but not enough inertia had been generated to sustain the effort without a strong leader guiding the process.

The key reason I was able to be successful in my internship was my ability to forge a strong working relationship with the decision-makers in different stakeholder groups. The director of the manufacturing organization commented to me in an exit interview that I was the first person to bridge the Test Engineering and Quality groups. The reason I was able to bridge the gap was that I offered myself as a resource to both groups. I tried to be perceived as an unbiased participant in the project, not a member of any political faction.

I also believe I was successful because I was confident enough to be myself. That meant I avoided falling into the "negative" norms I perceived in QWBS. I created agendas for my meetings and followed up with meeting minutes. I documented proposed experiments, decision criteria, data, and results, and distributed the information to all interested parties. I was willing to behave differently and be noticed for it. You need to operate within the cultural and managerial boundaries of the organization, but as a change agent, you sometimes need to avoid conformity.

7.0 Summary

Statistical process control tools, if leveraged effectively, can help manufacturing companies improve quality and reduce cost. To some, though, SPC sounds too complicated to implement. If you read journal articles on the topic, for example, you'll find that a wealth of research goes into determining the most appropriate methods for reducing the affects of autocorrelation on control chart performance. Time series modeling, autoregressive integrated moving average models, and other important aspects of SPC can make SPC seem too daunting to tackle.

But automated control charts with feedback to automatically adjust process tool parameters is not required to derive benefit from a statistical quality control program. Sometimes, just the process of developing control charts can yield positive benefits. At Qualcomm, analyzing and understanding the distribution of measurements in the OmniTRACS test process provided a wealth of information that wasn't evident in failure paretos. This information alone enabled the team to dramatically improve yields with little effort. As the organization becomes more comfortable and adept with the use of SPC, it may then find that more complicated statistical process control tools will add to its understanding of the process and enable it to monitor the process more effectively. But starting with a set of tools that can be understood and implemented by the organization is essential to the long-term success of a statistical quality control program.

The success of this project benefited from the existence of low-hanging fruit in the test process. The issues uncovered at ATP were relatively easy to address by changing some specification limits and eliminating some non-value added tests. And there is definitely more room for improvement. The question facing the QWBS organization is whether it wants to commit to the process of reducing variation until, as Deming (1986, p. 49) stated, "specifications are lost beyond the horizon." This requires more than a short-term project. It requires a change in the culture of the organization. Engineers need to be equipped with the tools to succeed, including training and software. And management must create incentives and provide sufficient resources to focus the organization on process improvement, rather than firefighting.

The success of the yield improvement team was a good first step in creating sustainable change within QWBS. Improving yields at ATP from 88% to 97% generated excitement and enthusiasm within the organization. The benefits of a stronger synergy between the Test Engineering and quality groups were tangible. And the OmniSPC Analysis application provides a tool to facilitate future process improvement projects.

But the ATP improvements are just the beginning. The yield improvement team now has the opportunity to extend the analysis performed at ATP to all other tests in the Omni manufacturing process. It should also continue the analysis correlating unit field performance to unit factory test performance to understand if the metrics used to evaluate product quality in the manufacturing process are useful. The annual savings generated by the project are commendable, but the potential long-term savings achievable through a commitment to continuous improvement make continued emphasis on the process a necessity.

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Appendix 1 Estimating Expected Process Fallout For a Given Cpk

The process capability ratio can be used to estimate expected fallout from a process in the absence of assignable causes. Assuming a normal distribution for the quality characteristic of interest, the following table can be used to look up the expected fallout rate of the process.

Cpk	Process Fallout (in defective PPM)	
	One-Sided Specifications	Two-Sided Specifications
0.25	226,628	453,255
0.50	66,807	133,614
0.60	35,931	71,861
0.70	17,865	35,729
0.80	8,198	16,395
0.90	3,467	6,934
1.00	1,350	2,700
1.10	484	967
1.20	159	318
1.30	48	96
1.40	14	27
1.50	4	7
1.60	1	2
1.70	0.17	0.34
1.80	0.03	0.06
2.00	0.0009	0.0018

Table 6 Value of the Process Capability Ratio (Cpk) and Associated Process Fallout for a Normally Distributed Process (in Defective PPM)

Using Table 6, I estimated the expected fallout rate (or rate of failures) for the three most frequently failing test attributes on each test station at ATP. I then multiply the fallout rate by the number of tests performed at the test station for the test attribute to estimate the number of units you would expect to fail given the number tested and the process capability. Table 7 summarizes the calculation for each test attribute and test station. The total number of failures expected in the data set below is 297 out of a total of 13,216 tests. This results in a 2.2% fallout rate.

The actual fallout rate seen at ATP over the time frame of this data set was 12%. The difference could be due to a significant number of failures due to assignable causes rather

than natural variation (though the assignable causes would need to be due to factors other than unit failures, as most of the 12% of failed units eventually pass on retest). More likely, the discrepancy is due to violations of the normality assumption underlying this analysis. Test attributes B and C are limited to integer values due to data transmission limitations, so the assumption of normality in the underlying data is not perfect. Several transformations were applied to the data in an attempt to better meet the normality criteria, but none were successful.

Test Attribute	Centerplate Supplier	Test Station	Cpk	# Tests	Expected Fallout (ppm)	Estimated Fallout
C	1	Tool 1	0.60	51	35931	2
B	1	Tool 1	1.06	47	750	0
A	1	Tool 1	1.32	47	38	0
B	1	Tool 2	0.30	105	180000	19
A	1	Tool 2	0.55	92	53000	5
C	1	Tool 2	0.59	110	37000	4
C	1	Tool 3	0.47	37	95000	4
B	1	Tool 3	0.78	33	10000	0
A	1	Tool 3	1.06	28	750	0
A	1	Tool 4	0.44	277	100000	28
C	1	Tool 4	0.72	295	13500	4
B	1	Tool 4	0.78	280	10000	3
C	2	Tool 1	0.71	861	12000	10
A	2	Tool 1	0.89	793	3800	3
B	2	Tool 1	1.05	816	900	1
A	2	Tool 2	0.59	1060	37000	39
C	2	Tool 2	0.64	1161	23000	27
B	2	Tool 2	0.66	1114	21000	23
C	2	Tool 3	0.58	667	40000	27
B	2	Tool 3	0.70	612	17865	11
A	2	Tool 3	0.98	586	1650	1
C	2	Tool 4	0.60	1447	35931	52
A	2	Tool 4	0.64	1324	23000	30
B	2	Tool 4	0.91	1373	3100	4

Total Tests 13216 Total Estimated Fallout 297
Resulting Fallout Rate 2.2%

Table 7 Estimated Fallout From ATP For Three Test Attributes

One way to reduce the expected fallout from a process is to center the process. If the mean is centered between the upper and lower specification limits, the process capability ratio increases. Table 8 calculates the fallout

Test Attribute	Centerplate Supplier	Test Station	Cpk	# Tests	Expected Fallout (ppm)	Estimated Fallout
C	1	Tool 1	0.75	51	23000	1
B	1	Tool 1	1.69	47	0.5	0
A	1	Tool 1	1.38	47	40	0
B	1	Tool 2	1.20	105	318	0
A	1	Tool 2	0.61	92	67000	6
C	1	Tool 2	0.70	110	35729	4
C	1	Tool 3	0.72	37	30000	1
B	1	Tool 3	0.94	33	5200	0
A	1	Tool 3	1.22	28	280	0
A	1	Tool 4	0.70	277	35729	10
C	1	Tool 4	0.89	295	7200	2
B	1	Tool 4	1.36	280	55	0
C	2	Tool 1	0.75	861	23000	20
A	2	Tool 1	1.05	793	1400	1
B	2	Tool 1	1.11	816	850	1
A	2	Tool 2	0.80	1060	16395	17
C	2	Tool 2	0.78	1161	20000	23
B	2	Tool 2	1.12	1114	775	1
C	2	Tool 3	0.66	667	50000	33
B	2	Tool 3	0.73	612	27000	17
A	2	Tool 3	1.09	586	1200	1
C	2	Tool 4	0.71	1447	32000	46
A	2	Tool 4	0.85	1324	10000	13
B	2	Tool 4	0.97	1373	3200	4

**Total Tests 13216 Total Estimated Fallout 202
Resulting Fallout Rate 1.5%**

Table 8 Estimated Fallout From ATP For Three Test Attributes With Centered Mean

Process capability can also be improved by increasing the specification range for each test attribute. Table 9 calculates the fallout from ATP that would be expected if the upper specification limit for each test attribute were increased from +3dB to +5dB and the

lower specification limit increased from -2dB to -5dB (effectively doubling the specification range for each test attribute)

Test Attribute	Centerplate Supplier	Test Station	Cpk	# Tests	Expected Fallout (ppm)	Estimated Fallout
C	1	Tool 1	1.20	51	159	4
B	1	Tool 1	3.09	47	0	0
A	1	Tool 1	2.43	47	0	0
B	1	Tool 2	1.74	105	0.09	0
A	1	Tool 2	1.15	92	240	16
C	1	Tool 2	1.36	110	30	1
C	1	Tool 3	1.05	37	900	27
B	1	Tool 3	1.87	33	0.001	0
A	1	Tool 3	2.03	28	0.0005	0
A	1	Tool 4	1.28	277	60	2
C	1	Tool 4	1.78	295	0.08	0
B	1	Tool 4	2.41	280	0.00005	0
C	2	Tool 1	1.39	861	18	0
A	2	Tool 1	2.06	793	0.00008	0
B	2	Tool 1	2.05	816	0.00006	0
A	2	Tool 2	1.55	1060	2.3	0
C	2	Tool 2	1.53	1161	3	0
B	2	Tool 2	2.00	1114	0.0009	0
C	2	Tool 3	1.10	667	484	24
B	2	Tool 3	1.28	612	60	2
A	2	Tool 3	2.08	586	0.00004	0
C	2	Tool 4	1.38	1447	24	1
A	2	Tool 4	1.66	1324	0.5	0
B	2	Tool 4	1.81	1373	0.01	0

**Total Tests 13216 Total Estimated Fallout 77
Resulting Fallout Rate 0.6%**

Table 9 Estimated Fallout From ATP For Three Test Attributes With Specification Range Doubled

The above analysis shows that the expected fallout rate at ATP could be reduced by 32% by centering the process for each attribute on each tool or it could be reduced by 74% by expanding the specification limits. Centering a process can be a difficult and expensive task. Expanding the limits is a relatively simple task, but one that should not be undertaken merely to improve test yields. The limits should be based on some set of

customer requirements or product performance requirements, not desired test yields. But if the specification limits were defined arbitrarily, then reviewing the justifications for the limits is certainly warranted.

30-7-17