# Printed Circuit Board Manufacturing

# Process Improvement

# Drill Optimization

by

Peter W. Lehmann

A Research Paper
Submitted in Partial Fulfillment of the
Requirements for the
Master of Science Degree
in

Management Techology

Approved: 4 Semester Credits

Researcher Advisor
Dr. John Dzissah

The Graduate School

University of Wisconsin-Stout

December, 2005

**The Graduate School**
**University of Wisconsin-Stout**
**Menomonie, WI**

**Author:** **Lehmann, Peter W.**

**Title:** ***Printed Circuit Board Process Improvement – Drill Optimization***

**Graduate Degree/ Major: MS Industrial Technology**

**Research Adviser:** **John Dzissah, Ph.D.**

**Month/Year:** **December, 2005**

**Number of Pages:** **47**

**Style Manual Used:** **American Psychological Association, 5th edition**

ABSTRACT

This research project served as a means to improve quality and drill machine utilization at a Chippewa Valley, Wisconsin company. This Chippewa Valley company is a printed circuit board manufacturer that was listed on Fortune Magazine's 100 fastest growing companies. Although, this company is a relatively new company, its manufacturing facilities have been operating in excess of twenty years under different company names. These facilities have produced printed circuit boards for the fastest computers in the world. Even with vast experience, future designs and market competitiveness demand better drill registration and higher yields.

The Graduate School

University of Wisconsin Stout

Menomonie, WI

Acknowledgments

I would like to thank my family for supporting me through this research project. My colleagues provided much encouragement and insight during this process. Dr. John Dzissah was valuable resource during this project he created a positive environment for an enjoyable learning experience. To Dr. Wallace "Chuck" Carlson, an undergraduate advisor, mentor, and friend since the start of my UW-Stout years.

TABLE OF CONTENTS

# List of Tables

# List of Figures

# Chapter I: Introduction

This Chippewa Valley Wisconsin company is a manufacturer of printed circuit boards with approximately 1,900 employees in three manufacturing plants, and a world wide customer base. This company was founded in 1999 with the merger of Power Circuits and Pacific Circuits. In 2005, Fortune Magazine's list of 100 fastest growing companies included this company.

The plant has 230,000 square feet of manufacturing area and employs approximately 1,100 people and has operated under several different names. The building was originally constructed and operated by Cray Research in 1989. Cray Research sold the operations to Johnson Matthey in 1996 and was added to the Advanced Circuits Division. In 1999, Honeywell purchased the Advanced Circuits Division and after Honeywell determined printed circuit board manufacturing was not a core competency, the Chippewa Valley facility was sold in December 2002. During these changes, the Chippewa Valley plant has manufactured rigid print circuit boards. Initially a captive manufacturing facility, this quickly changed when Johnson Matthey's management, converted a majority of manufacturing over to Intel Pentium chip carrier. Since then customer diversification has continued to be a focus to improve long range competitiveness.

## Background of the Problem

Drill utilization is below expectations, although this problem is not unique to this Chippewa Valley company as other researchers have identified drill machine utilization below 70% (Yu, Shih, Pfund, Carlyle, and Fowler 2002). Manufacturing tools used to determine drill registration are limited due to an inability to discriminate individual layer registration. Utilizing a real time x-ray system, operators review six panels to determine necessary corrections in order to optimize drill registration. Due to the complexity of printed circuit boards and limited available panel space, operators are not able to evaluate annular ring on every layer. Instead operators are reviewing a gray scale image to determine the relative location of each individual layer. Drill machine time is lost while panels are being inspected. This also leads to a biased result as the results for a lot of forty eight panels is based on the first six panels processed.

Statement of the Problem

Drill registration impacts several areas of printed circuit board manufacturing. Drill machine utilization is negatively impacted due to lost machine time while operators determine drill scale and machine offsets. A portion of product scrap is due to internal shorts resulting from drill registration.

Purpose of the Study

The purpose of this study is to increase drill machine utilization and improve yields at the Chippewa Valley Wisconsin company. Global competition is driving the need to reduce cost structure and improve quality. Therefore, to remain competitive in this market, process improvements are needed in the drilling department. A baseline of existing performance metrics will be established and "quality tools" will be used to implement quality improvements.

Assumptions of the Study

The first assumption: Management has determined a need for improvements in machine utilization of drilling machines.

The second assumption: Process improvement solutions did not involve any human subjects.

The third assumption: Management will allocate required capital to acquire new equipment.

The fourth assumption: This study applies only to this manufacturing facility.

The fifth assumption: Product scheduling is not being considered.

Definition of Terms

Layer: A resin system with copper on both sides. The resin system with copper ranges in thickness from .003 inches to .010 inches.

Drill Machine: A computer numeric controlled drill machine with six stations that is capable of drilling six panels at a time (one load).

Drill Program: A vector program that positions the drill machine for proper hole locations.

Scaled Drilled Program: A drill program that has the drill locations moved proportionally to correspond too layer movement.

Response variable: The variable being investigated, also called the dependent variable.

Primary variables: The controllable variables believed most likely to have an effect.

Background variables: Variables that are uncontrollable.

Real time x-ray: An x-ray that allows for visual inspection of a printed circuit board.

Registration: The spatial relationship between the internal pad and drill holed.

Annular Ring: The minimum space between the edge of the internal pad and edge of drilled hole (see Figure 1).

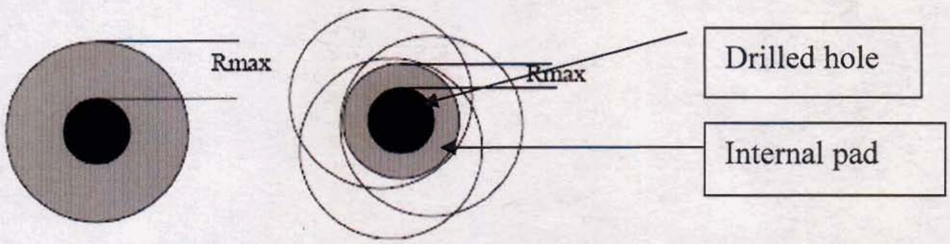



Figure 1: Annular Ring

Limitations of the Study

This field project will provide a mechanical solution to improve the drill department's operating efficiency. A mature quality system has reports with defect rates related to internal shorts. Likewise, a drill machine utilization reporting system is currently available. Time studies are available for certain process elements related to the drilling department. Management will review requests for capital expenditures that may be required as part of this study.

Methodology

Several data analysis tools will be incorporated into this field project. First, a base line will be established for lost drill machine time. A defect rate will be established for internal registration.

As part of the acceptance criteria, a Gage R&R study will be completed and an analysis of variance will analyze different x-ray target acquisition methods.

# Chapter II: Literature Review

## Introduction

The literature review will cover three areas: 1) providing background information of a printed circuit board, 2) manufacturing process overview, and 3) information related to gage repeatability and reproducibility study and one way ANOVA.

## Printed Circuit Board Background

Although unknown by most people, our daily lives are continuously in contact with printed circuit boards or otherwise referred to as printed wiring board. A short list of appliances that utilize a printed circuit board are alarm clocks, radios, televisions, DVD players, stoves, and microwave ovens. Interconnection Technology Research Institute staff (1999) describes printed circuit boards:

"The Printed Wiring Board (PWB) is the foundation of all electrical equipment. The PWB is a structural component that allows the intended physical function of the equipment to be accomplished, as well as an electrical component that interconnects all of the other electrical components. The importance of the PWB continues to increase as new equipment comes to market with increased functions, new packaging, and increased performance." (p. 2)

Dr. Paul Eisler developed the first practical circuit board in 1942 (Scarlett, 1985). Although wide spread application of this design did not take off until the 1950's, due to the lack of suitable material to construct the circuit boards. This initial double sided circuit board satisfied connection requirements for existing tube technology. When transistors starting replacing tubes in the 1950's the functionality of the double sided circuit board became a limiting factor in electronic design. In 1961, Hazeltyne patented the multilayer printed circuit board technology. This technology is still the basis for multilayer printed circuit boards built today. Since 1961, technology changes have been made in raw material design and manufacturing equipment and these improvements have led to smaller circuit board sizes and increased operating speeds of electronic equipment.

Printed Circuit Board Manufacturing

After receiving an order for a particular printed circuit board design, artwork and layers are released to manufacturing. The layer manufacturing process is to produce copper traces, or ground shields, on each side. There are several manufacturing operations required the layer is coated with photoresist which is than imaged by exposing the artwork to the photoresist, then the image is developed by removing the unexposed photoresist from the layer. Next the layer is etched to remove copper, which provides the desired traces. Finally the remaining photoresist is stripped from the layer. An automated optical inspection of the layers is completed as an inspection process, before layers are used in down stream processing. At this time certain defects can be repaired to improve yields. At lamination layers are laid up in sequential order with a piece of epoxy resin between them. Generally a six panel stack up to a book, which may be up to 60 layers, is placed in a lamination press opening of which there are eight openings per press. During lamination, the press applies pressure to the stack of layers, a vacuum is drawn, and heat is applied. This allows the resin to flow without voids.

The board is now ready for outer layer manufacturing. In the drilling department panels have holes drilled ranging in size from .008" to .250". A finished drilled panel may have between 20,000 to 55,000 holes, depending on the size and configuration of the panel. A desmear operation prepares the holes for plating. After the holes are plated an external image is applied following a similar process that was used for internal layer circuitry. The appropriate surface finish is then applied, followed by soldermask. Panels are routed to remove individual parts. Parts are then electrical tested and finally packaged for shipment to the customer.

Gage R&R and ANOVA

There are a number of well documented statistical techniques that have been used to improve quality in United States manufacturing. "By one count, there are over 400 continuous improvement tools." (Pyzdek, 1999) Seven tools that are commonly used are: pareto charts, cause and effect diagrams, flow charts, control charts, check sheets, scatter diagrams, and histograms. In recent years a summation of these tools has been labeled Six Sigma which is a data driven methodology to reduce defects in any. For this study just two design of experiment techniques will be reviewed, they are measurement system analysis or Gage R&R and analysis of variance.

The first design of experiment was completed in the agricultural and biological sciences by Sir Ronald A. Fisher (Montgomery, 1996). During the 1930's industrial application of design of experiments were applied in the British textile and woolen industry. In the United States design of experiments were introduced to industry following World War II. "The semiconductor and electronics industry has also used experimental design methods for many years with considerable success." (Montgomery, p. 17). Due to increasing competitive pressures from other countries on United States manufacturing, there is a renewed interest in using design of experiments.

To improve a manufacturing process an experimental design may be used for the following reasons (Montgomery, 1996).

1) Improved process yields.
2) Centering a process to nominal or target value.
3) Reduced development time.

4) Improve operating costs.

While developing a new product, there may be several reasons to apply an experimental design (Montgomery, 1996).

1) To consider alternative materials.

2) To ensure the product is designed for a variety of working conditions.

3) Key product design characteristics can be identified.

4) Impact of varying design configurations can be evaluated.

Statistical design of experiments is a process of planning an experiment to ensure the most efficient test method is used (Montgomery, 1996). Terminology used in experimental designs reflects its agricultural origin (Pyzdek, 1999). Pyzdek describes the relationship of the terminology as follows:

"The experimental area was literally a piece of ground. A block was a smaller piece of ground with fairly uniform properties. A plot was smaller still and it served as the basic unit of design. As the plot was planted, fertilized and harvested it could be split simply by drawing a line. A treatment was actually a treatment, such as the application of fertilizer." (p. 304)

Since a well planned experiment is vital for success, Juran (p. 27-4, 1974) provides the following table, showing some requisites and tools for sound experimentation (Table 1).

Table 1: Some Requisites and Tools for Sound Experimentation

| Requisites | Tools |
|---|---|
| 1. The experiment should have carefully defined objectives. | 1. The definition of objectives requires all the specialized subject-matter knowledge of the experimenter, and results in such things as:<br>a. Choice of factors, including their range<br>b. Choice of experimental materials, procedure, and equipment<br>c. Knowledge of what the results are applicable to. |
| 2. As far as possible, effects of factors Should not be obscured by other variables. | 2. The use of an appropriate experimental pattern helps to free the comparisons of interest from the effects of uncontrolled variables, and simplifies the analysis of results |
| 3. As far as possible, the experiment should be free from bias (conscious or unconscious) | 3. Some variables may be taken into account by planned grouping. For variables not so taken care of, use randomization. The use of replication aids randomization to do a better job |
| 4. Experiment should provide a measure of precision (experimental error)* | 4. Replication provides the measure of precision; randomization assures validity of the measure of precision |
| 5. Precision of experiment should be sufficient to meet objectives set forth in requisite 1 | 5. Greater precision may be achieved by: refinements of technique, experimental pattern (including planned grouping), replication |

* Except where there is well-known history of the measurement process.

A checklist for planning an experiment design is provided by Juran (p 27-5):

A. Obtain a Clear Statement of the Problem

1. Identify the new and important problem area
2. Outline the specific problem within current limitations
3. Define exact scope of the test program
4. Determine relationship of particular problem to whole research or development program

B. Collect Available Background Information

1. Investigate all available sources of information

2. Tabulate data pertinent to planning new program

C. Design the Test Program

1. Hold a conference of all parties concerned

a. State the propositions to be proved

b. Agree on magnitude of differences considered worthwhile

c. Outline the possible alternative outcomes

d. Choose the factors to be studied

e. Determine practical range of factors and specific levels at which test will be made

f. Choose the end measurements which are to be made

g. Consider the effect of sampling variability and of precision of test methods

h. Consider possible interrelationships (or "interactions") of the factors

i. Determine limitations of time, cost, materials, manpower, instrumentation, and other facilities and of extraneous conditions such as weather

k. Consider human-relations angles of the program

2. Design the program in preliminary form

a. Prepare a systematic and inclusive schedule

b. Provide for stepwise performance or adaptation of schedule if necessary

c. Eliminate effect of variables not under study by controlling, balancing, or randomizing them

d. Minimize the number of experimental runs

e. Choose the method of statistical analysis

f. Arrange for orderly accumulation of data.

3. Review the design with all concerned

a. Adjust the program in line with comments

b. Spell out the steps to be followed in unmistakable terms

D. Plan and Carry out the Experimental Work

1. Develop methods, materials, and equipment

2. Apply the method or techniques

3. Attend to and check details; modify methods if necessary

4. Record any modification of program design

5. Take precautions in collection of data

6. Record progress of the program

E. Analyze the Data

1. Reduce recorded data, if necessary, to numerical form

2. Apply proper mathematical statistical techniques

F. Interpret the Results

1. Consider all the observed data

2. Confine conclusions to strict deductions from the evidence at hand

3. Test questions suggested by the data by independent experiments

4. Arrive at conclusions as to the technical meaning of results as well as their statistical significance

5. Point out implications of the findings for application and for further work

6. Account for any limitations imposed by the methods used

7. State results in terms of verifiable probabilities

G. Prepare the Report

1. Describe work clearly, giving background, pertinence of problems, meaning of results
2. Use tabular and graphic methods of presenting data in good form for future use
3. Supply sufficient information to permit reader to verify results and draw his own conclusion
4. Limit conclusions to objective summary of evidence so that the work recommends itself for prompt consideration and decisive action

An analysis of variance was selected to test the means of several measurements obtained by the drill optimizer (Montgomery, 1994). Since a single factor is being investigated, an one-way or single-factor analysis of variance model will be used. "The ANOVA procedure will distinguish the extent of variation we can ascribe to ordinary sampling error, and the variation we can ascribe to the factor …" Craver (p. 185, 2004). When using an one-way ANOVA, the following assumptions must be true: 1) samples are independent 2) normal distribution 3) equal variances are shared by the populations. Minitab provides both a graphical description and descriptive data. Graphical charts that are beneficial in assisting with analyzing data are dot diagrams, histograms, and box-and-whisker plots (Montgomery). These charts provide the experimenter a quick look at the central tendency of the observations.

Descriptive data provided by Minitab is broken in to two parts (Carver, 2004). A common ANOVA table is provided first. Here the experimenter is provided a P-Value which is useful for hypothesis testing (Montgomery, 1994). The experimenter establishes a statistical hypothesis for the problem in a null hypothesis and alternative hypothesis.

The null hypothesis states what is believed to be true. The P-Value is the smallest level of significance that would lead to the rejection of the null hypothesis. The lower the P-Value the greater the likely hood of rejecting the null hypothesis. There are two errors associated with testing null hypothesis. Juran (1974) explains the risk as follows:

1. Reject the hypothesis when it is true. This is called the "type I error" or the "level of significance" and is denoted by α.

2. Accept the hypothesis when it is false. This is called the "type II error" and is denoted by β. (p. 22-33)

The test statistic for an one-way ANOVA is F-distribution and is also provided in the top portion of the table. F is the ratio of the variances. Minitab also provides data related to the sample size, mean, and standard deviation in the lower portion of the chart.

A gage repeatability and reproducibility study is completed to determine the sources of variation in the measurement system. Generally, three sources of error are identified: part to part, operator, and gage. Two standard methods for a gage repeatability and reproducibility study are average and range method and analysis of variance method (Kappele and Raffaldi, 2005). The Automotive Industry Action Group supports using the average and range method which leads to its popularity. Calculating an analysis of variance is more complex but computer software applications can remove most of this burden. Both methods provide a means to evaluate the measurement system error.

When using Minitab to perform a Gage R&R study, several key values are generated. The total Gage R&R is labeled with an A in table 1. This value represents the percentage of contribution due to repeatability and reproducibility. Item B labels the part-to-part contribution to the total variation. The part-to-part contribution must be larger than the total Gage R&R contribution for an acceptable gage. A gage's ability to distinguish categories is the final key value and is labeled with a C. According to AIAG, this value should be 5 or larger for an acceptable gage.

Table 2: Example of Minitab Gage R&R Results

| Source | VarComp | (of VarComp) | |
|---|---|---|---|
| Total Gage R&R | 0.0000005 | 6.38 ← | A |
| Repeatability | 0.0000005 | 6.38 | |
| Reproducibility | 0.0000000 | 0.00 | |
| Part-To-Part | 0.0000072 | 93.62 ← | B |
| Total Variation | 0.0000077 | 100.00 | |

| Source | StdDev (SD) | Study Var (6 * SD) | %Study Var (%SV) | %Tolerance (SV/Toler) |
|---|---|---|---|---|
| Total Gage R&R | 0.0006990 | 0.0041937 | 25.27 | 20.97 |
| Repeatability | 0.0006990 | 0.0041937 | 25.27 | 20.97 |
| Reproducibility | 0.0000000 | 0.0000000 | 0.00 | 0.00 |
| Part-To-Part | 0.0026766 | 0.0160597 | 96.76 | 80.30 |
| Total Variation | 0.0027664 | 0.0165982 | 100.00 | 82.99 |

Number of Distinct Categories = 5 ← C

Because the operator cannot influence the measurement, automated gaging has increased in popularity, (Kappele and Raffaldi, 2005). An instantaneous method calculates only the repeatability and equipment variation reported as a percentage of total tolerance. An acceptable Gage R&R percentage is 10% or less. This method uses at least 10 parts and three trials. To complete the calculations follow the following steps:

1) Calculate the standard deviation for each part ($s_1$, $s_2$, $s_3$, etc.)
2) Square the standard deviation for each part above. This is the variance for each part. ($s_1^2$, $s_2^2$, $s_3^2$, etc.)
3) Calculate the average variance. ($[s_1^2 + s_2^2 + s_3^2 + \text{etc.}] / N$, where N is the number of parts.)

4) Take the square root of the average variance in the previous step to obtain the study standard deviation.

5) Divide the standard deviation by the Duncan $c_4$ value if using less than 10 trials. See the table, "Instantaneous Method $c_4$ Values" in Appendix D.

6) Multiply the adjusted value from the previous step by the standard deviation spread, usually 5.15.

7) Divide the value from the previous step by tolerance (the Upper Specification Limit (USL) minus the Lower Specification Limit (LSL) and multiply by 100. (Kappele and Raffaldi p. 40-41)

# Chapter III: Methodology

## Introduction

This chapter will provide insight in to the methodology utilized to develop a process improvement plan in this study. Several different engineering tools will be utilized in developing a solution to reduce drill registration failures and to improve drill utilization. As circuit board designs are becoming more complex, existing methods of establishing drill registration are becoming more time consuming and inaccurate. It is the researcher's belief that a mechanical device is available that will improve drill registration and eliminate lost drill machine time. Data provided from this solution will also remove the work load constraint in the dry lab for layer scale cross sections.

## Method of Study

From the search of available solutions, the machines were evaluated based on critical operating characteristics. Using the information gathered on each manufacturer's machine, a machine was selected for procurement. Once the equipment was on site, the machine qualification and implementation process was started. Since this equipment was performing an inspection process, a gage repeatability and reproducibility study was completed. Several different machine vision target acquisition methods were available on the Fein Focus and these methods were evaluated using a one way ANOVA.

## Sample Selection

This study includes the drilling department at the Chippewa Valley manufacturing site. This department was selected based on low machine utilization numbers and scrap due to drill registration. There was a work load constraint in the dry lab due to the number of request for layer registration cross sections. At any given time there may be an excess of 150 cross sections in the dry lab's queue, with each cross section requiring between four and six man hours to process, depending on layer count.

Method of Analysis

A Gage R&R was completed by measuring a set of twelve panels three times. Machine vision acquires all data related to the product results. Reproducibility is not a viable component of this study. Due to machine automation, an operator is not able to influence panel results. As a result of the machine design, the x-axis and y-axis are independent of the other. The table is driven by a linear motor in the x-axis and the x-ray camera is moved in the y-axis by another linear motor. The Fein Focus system also provides a measurement of annular ring (R-min) which is derived from calculating layer movement in each corner of the panel and then comparing the drill scale location to the pad size. So a Gage R&R was completed on each axis and the annular ring.

An one way ANOVA was required to analyze X scale, Y scale, and annular ring results between the different machine vision targeting methods. This will provide insight if the results came from the same population using different targeting methods.

Baseline data of drill machine utilization will be compared before and after installation of drill optimizer.

Instrumentatior.

There are many different quality software packages available for data analysis. This company has standardized on Minitab Release 14 for data analysis.

System Evaluation

**Optek Innervision**

This system provides the ability to measure internal targets using x-ray inspection (see Figure 2). Innervision requires an operator to load each panel individually which is unacceptable in a high volume production manufacturing setting. This system is unable to drill new tooling for drilling which is required to adjust for layer skew. This system is built with a sealed x-ray tube which runs until failure at which time a service technician would be required for installation of a new x-ray tube. This component has the shortest mean time between failure value.


Figure 2: Optex Optimization Equipment

**Multiline XRT 1000 Optiline PL**

Multiline's system (see Figure 3) was used in another manufacturing facility. This system has the ability to drill tooling holes to be used at drilling but the x-ray system is only able to measure layer movement in single axis during an inspection cycle. To measure both axis of the panel two separate machine cycles are required and means tooling holes are based on layer movement in a single axis. Panel loading and unloading is completed by an operator. X-ray tube maintenance requires a service technician.

Figure 3: Multiline Optimization Equipment

**Fein Focus System FXS 100.82**

The FXS 100.82 system (see Figure 6) from Fein Focus has several critical characteristics not found on the other systems. First, the system is able to acquire layer movement data in both axis's in a single inspection. Secondly, the system is designed with an automated panel load and unload, which is a necessary in high volume manufacturing. Tooling holes for drilling are based on layer skew and shift in all directions. A unique design concept of over - under tables, which allows for increased production with no impact on manufacturing floor space. Maintenance of the x-ray system can be completed by in-house employees due to the unique construction. Machine calibration is easily completed again by in-house employees.

Fein Focus has provided several different machine vision capabilities to allow for development of a process that is suited for each individual company (see Figure 4). The 2 x 2 mm square pad is referred to as the quad pad. This construction provides for the fastest data acquisition since all the quad pads are stacked above each other, the vision system measures each side of the quad pad to obtain layer shift. With this method, individual layer scale factors are not obtained since the system is acquiring an average location to the entire stack up. Coupon sets are the 1.5 mm diameter pads and are located in a unique location on each layer in each corner of the panel. These targets provide information relative to the front to back registration of every layer and layer shift which provides the most detailed information. The last targeting method is to measure every other target. This method results in measuring just a single pad from each layer and relies on front to back registration to be controlled in up stream processes.

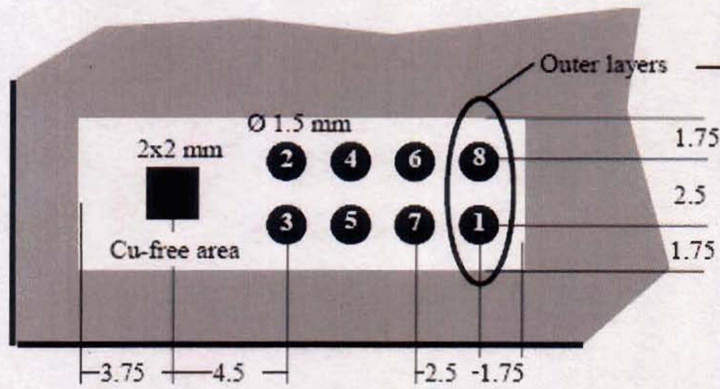



Figure 4: Machine Vision Targets

The machine vision targets are located in all four corners of the panel with this configuration the system is able to calculate more accurately the best fit drill program. There are several common types of misalignment which are illustrated in Figure 5.

System 100.82 is the only system that was able to acquire this much information with a single inspection cycle.

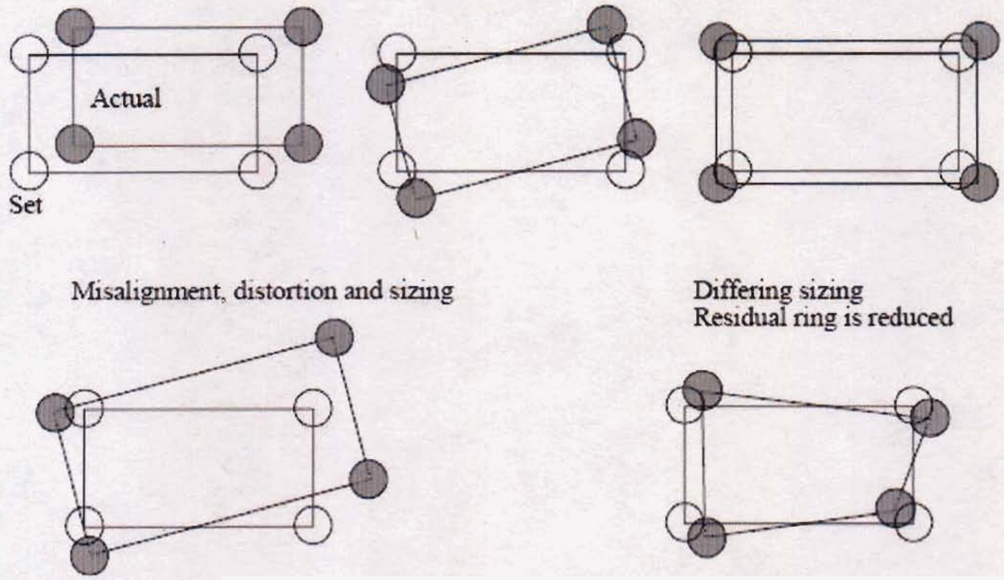



Figure 5: Common alignment errors

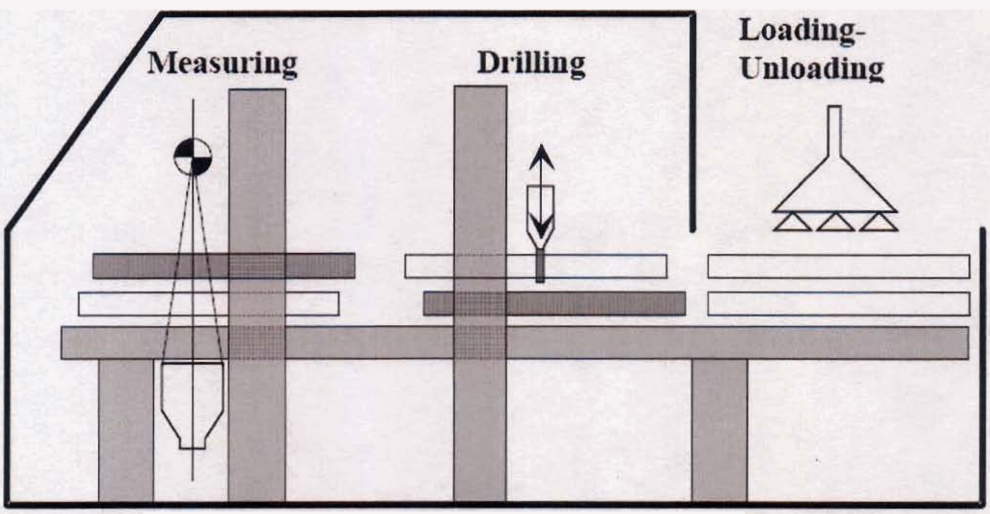



Figure 6: Fein Focus Optimization Equipment

# Chapter IV: Results

## Introduction

This study utilized engineering techniques from several disciplines to improve the operating efficiency of the drilling department in a Chippewa Valley Wisconsin company. A gage repeatability and reproducibility study was performed to determine machine stability. Then an analysis of variance study was used to assist in determining the optimal machine vision targeting method and cycle time performance.

## Available Solutions

Three viable solutions were identified, after researching the available automated drill registration systems, the system manufacturers were Optek, Multiline, and Fein Focus. Each system provided a method to obtain the desired result of eliminating the timely task of inspecting coupons on individual panels. The 100.82 system from Fein Focus was selected based on several factors: automated material handling on this system was significantly more advanced than the other systems, daily production on this system will be 1400 panels, and an over - under table design. This system is able to multitask, as one table is completing the x-ray inspect, the other table is drilling tooling holes and loading. Fein Focus has a unique x-ray system that provides higher quality images which is important when working with different resin materials and copper thicknesses. Fein Focus's image processor is also able to automatically adjust the contrast level for the x-ray tube wear. Preventive maintenance of this system was unique that the x-ray tube is serviceable by in-house employees. This component has the shortest mean time between failure which leads to the requirement of being serviceable.

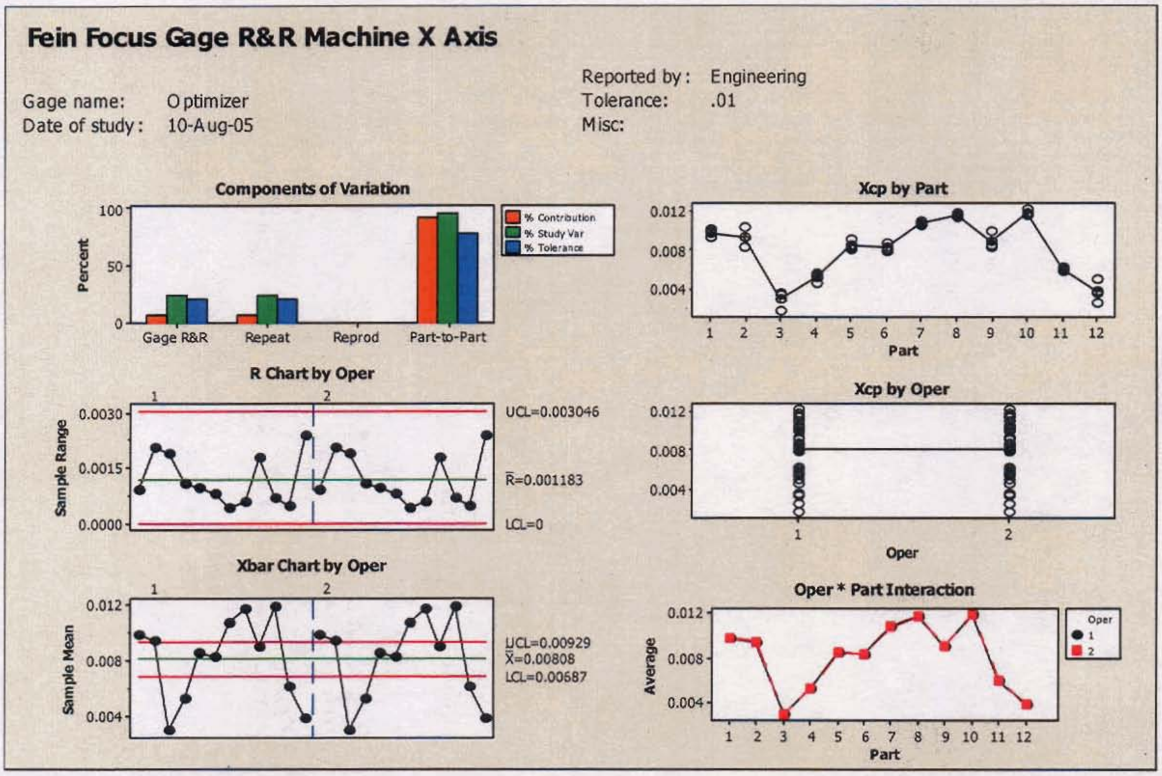
Data Analysis

Gage R & R

Since there are two distinct targets that Fein Focus can acquire, it was necessary to complete a Gage R & R utilizing both methods.

Three unique part characteristics are obtained by the optimizer, so data was collected on each characteristic. The next three tables are based on data using the coupon set with data for x axis and y axis being reported as scale factor for each panel in that axis, reported as a percentage. A movement of .01% translates to .0001" of linear movement across the panel. Process tolerance for x axis and y axis was .01%. The third graph is based on remaining ring (annular ring), which is reported in thousandths of an inch. This value is generated based on data collected on target location, rotation, and fit with the other layers. Process tolerance for R min was established at .0005".

Table 3: Gage R&R X Axis

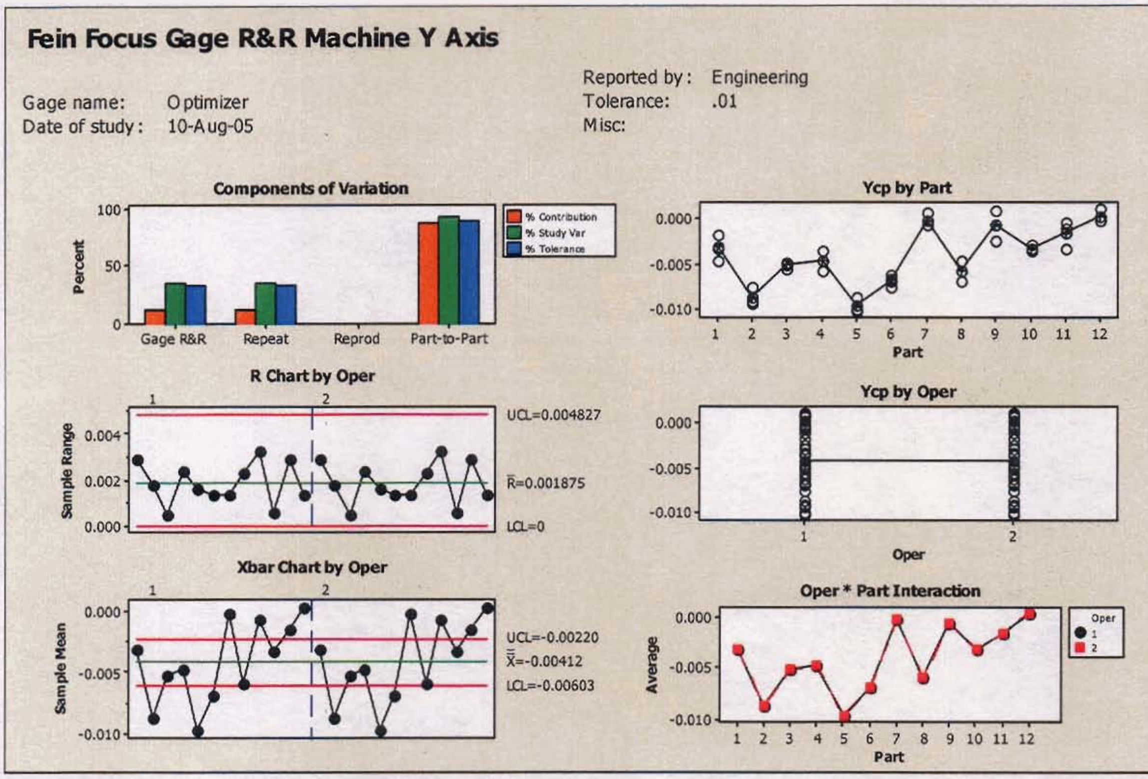



| Source | VarComp | %Contribution (of VarComp) |
|---|---|---|
| Total Gage R&R | 0.0000005 | 6.38 |
| Repeatability | 0.0000005 | 6.38 |
| Reproducibility | 0.0000000 | 0.00 |
| Part-To-Part | 0.0000072 | 93.62 |
| Total Variation | 0.0000077 | 100.00 |

| Source | StdDev (SD) | Study Var (6 * SD) | %Study Var (%SV) | %Tolerance (SV/Toler) |
|---|---|---|---|---|
| Total Gage R&R | 0.0006990 | 0.0041937 | 25.27 | 20.97 |
| Repeatability | 0.0006990 | 0.0041937 | 25.27 | 20.97 |
| Reproducibility | 0.0000000 | 0.0000000 | 0.00 | 0.00 |
| Part-To-Part | 0.0026766 | 0.0160597 | 96.76 | 80.30 |
| Total Variation | 0.0027664 | 0.0165982 | 100.00 | 82.99 |

Number of Distinct Categories = 5

Table 4: Gage R&R Machine Y Axis

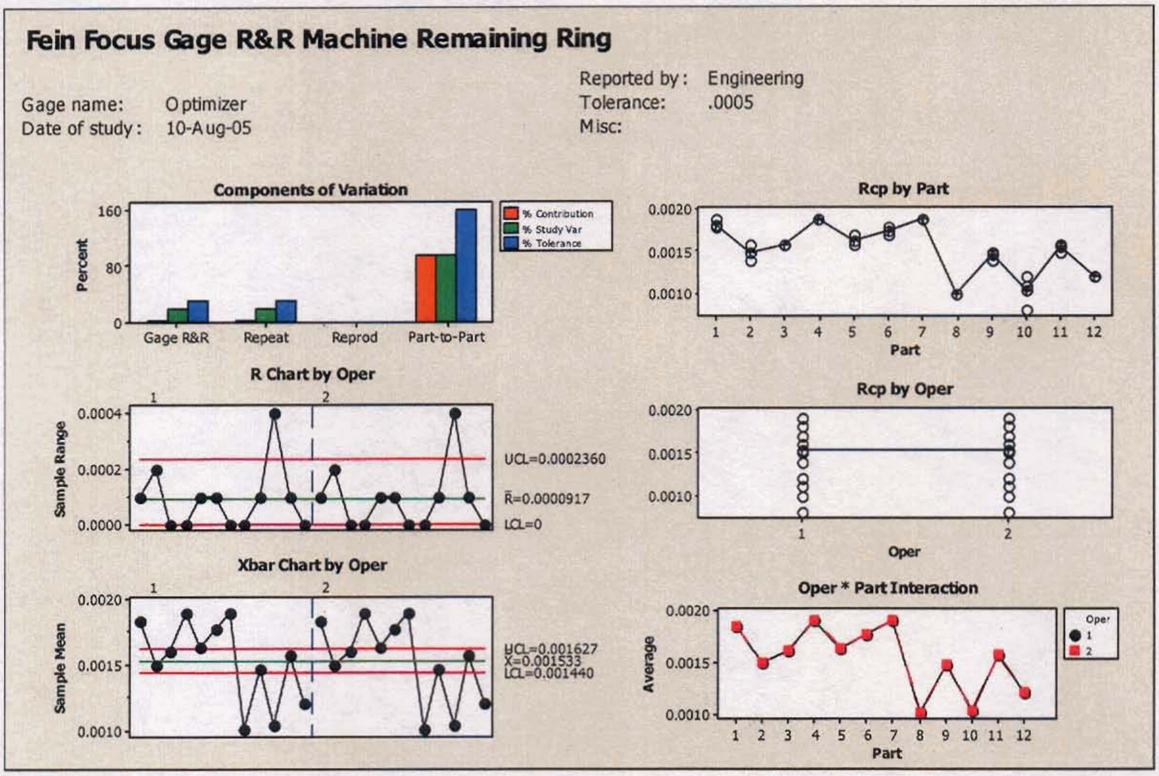



| Source | VarComp | %Contribution (of VarComp) |
|---|---|---|
| Total Gage R&R | 0.0000012 | 11.89 |
| Repeatability | 0.0000012 | 11.89 |
| Reproducibility | 0.0000000 | 0.00 |
| Part-To-Part | 0.0000091 | 88.11 |
| Total Variation | 0.0000103 | 100.00 |

| Source | StdDev (SD) | Study Var (6 * SD) | %Study Var (%SV) | %Tolerance (SV/Toler) |
|---|---|---|---|---|
| Total Gage R&R | 0.0011075 | 0.0066450 | 34.48 | 33.23 |
| Repeatability | 0.0011075 | 0.0066450 | 34.48 | 33.23 |
| Reproducibility | 0.0000000 | 0.0000000 | 0.00 | 0.00 |
| Part-To-Part | 0.0030149 | 0.0180896 | 93.87 | 90.45 |
| Total Variation | 0.0032119 | 0.0192714 | 100.00 | 96.36 |

Number of Distinct Categories = 3

Table 5: Gage R&R Remaining Ring (Annular Ring)




| Source | VarComp | %Contribution (of VarComp) |
|---|---|---|
| Total Gage R&R | 0.0000000 | 3.90 |
| Repeatability | 0.0000000 | 3.90 |
| Reproducibility | 0.0000000 | 0.00 |
| Part-To-Part | 0.0000001 | 96.10 |
| Total Variation | 0.0000001 | 100.00 |

| Source | StdDev (SD) | Study Var (6 * SD) | %Study Var (%SV) | %Tolerance (SV/Toler) |
|---|---|---|---|---|
| Total Gage R&R | 0.0000541 | 0.0003249 | 19.76 | 32.49 |
| Repeatability | 0.0000541 | 0.0003249 | 19.76 | 32.49 |
| Reproducibility | 0.0000000 | 0.0000000 | 0.00 | 0.00 |
| Part-To-Part | 0.0002687 | 0.0016119 | 98.03 | 161.19 |
| Total Variation | 0.0002741 | 0.0016444 | 100.00 | 164.44 |

Number of Distinct Categories = 6

Gage R&R results from both machine vision targets are summarized in table 6.

The coupon set provides acceptable Gage R&R results in all three characteristics.

Although the number of distinct categories in the y axis is below AIAG recommendation of 5, the total Gage R&R as compared to part to part variation is still acceptable. Data reported for the two other characteristics had acceptable results for distinct categories. Gage R&R results completed utilizing the quad pad targeting method is in Appendix A.

Table 6: Summary of Gage R&R results

| | **X axis** | | |
|---|---|---|---|
| | Total Gage R&R | Part to Part | Distinct Categories |
| Quad Pad | 12.52 | 87.48 | 3 |
| Coupon Set | 6.38 | 93.62 | 5 |
| | **Y axis** | | |
| Quad Pad | 35.04 | 64.96 | 1 |
| Coupon Set | 11.89 | 88.11 | 3 |
| | **Annular Ring** | | |
| Quad Pad | 2.26 | 97.74 | 9 |
| Coupon Set | 3.9 | 96.1 | 6 |

ANOVA

An one way ANOVA was completed to test for a statistical difference in machine targeting methods. Due to machine capacity constraints, it is not possible to measure every layer for every panel. With this consideration, the researcher sought to optimize throughput by using different machine targeting methods. The following abbreviations will be used cp means coupon set, qp means quad pad, and eo means every other layer. Table 7 summarizes the results of the different machine targeting methods.

Table 7: ANOVA Target Method Results

| | | |
|---|---|---|
| | **X axis** | |
| | F | P |
| CP - QP | 23.89 | 0 |
| CP - EO | 1.28 | 0.271 |
| | **Y axis** | |
| CP - QP | 12.34 | 0.001 |
| CP - EO | 0.82 | 0.374 |
| | **Annular Ring** | |
| CP - QP | 1163.92 | 0 |
| CP - EO | 4.28 | 0.051 |

ANOVA Replication

A replicated test was completed to validate differences between machine targeting methods (see Appendix B). Although coupon set provides optimum results, this measurement method would not provide the required daily panel production requirements.

Analyzing test data reveals several things. Statistically there is a difference between the two measurement methods of coupon set versus quad pad. Differences in the scale factors for x axis and y axis although statistically different and resulted in panels not being fully optimized when using quad pad targets. The every other layer target method provided the best result for annular ring which is critical to the customer.

Target Acquisition Time Study

Data was collected for time requirements for acquiring data for each targeting method to determine machine capacity. The data summarized in table 8 does not include time to load and unload panels from the machine.

Table 8: Time Study of Different Target Acquisition

| Measurement Method | Panels | Layers | Cycle Time in seconds | Cycle Time / Panel | Cycle Time / Layer |
|---|---|---|---|---|---|
| All Layers | 12 | 18 | 610 | 50.83 | 2.82 |
| Every Other | 12 | 18 | 388 | 32.33 | 1.80 |
| Quad Pad | 12 | 18 | 263 | 21.92 | 1.22 |

Since product mix is varies substantially, different machine capacities were generated based on layer count with this data being summarized in table 9. Current estimated machine up time is 96% or 23.04 hours. The every other layer targeting method provided required panel production based on product mix.

Table 9: Time Study based on Product Mix

| Layers | | Panels | Run Time | Panels | Run Time | Panels | Run Time |
|---|---|---|---|---|---|---|---|
| 18 | All Layers | 1400 | 19.83 | 1600 | 22.66 | 1700 | 24.07 |
| 18 | Every Other | 1400 | 12.63 | 1600 | 14.44 | 1700 | 15.34 |
| 18 | Quad Pad | 1400 | 8.58 | 1600 | 9.81 | 1700 | 10.42 |
| 24 | All Layers | 1400 | 24.22 | 1600 | 27.67 | 1700 | 29.41 |
| 24 | Every Other | 1400 | 15.43 | 1600 | 17.62 | 1700 | 18.73 |
| 24 | Quad Pad | 1400 | 10.47 | 1600 | 11.97 | 1700 | 12.72 |

Drill Machine Utilization

Comparing the average drill room performance from 5-Jun-04 through 11-Dec-04 versus 8-Jan-05 through 18-Jun-05 shows an average increase of 2.7% based on 69.7% versus 72.4% respectively (see table 10). This improvement is based on scaling drill programs before panels are on drill machines and reduction of number of times panels are taken off the machine for x-ray inspection. After x-raying the first coupons, if it was necessary to scale a drill program, the drill machine may be waiting for 20 minutes to three hours depending on the complexity of the request. Generally orders are ran on two to four drill machines which meant several machines would be waiting for the operator to optimized the drill program.

Table 10: Drill Machine Utilization

| Before | After |
|---|---|
| 69.7 | 72.4 |

Processing panels at drill prior to the optimizer required the operator to validate any adjustments made in drill offset or drill scale. It was not uncommon to x-ray in-process coupons twice or more for difficult product. Sometimes another load of panels would be started due to the need for more coupon inspections prior to starting the drill program into the live part.

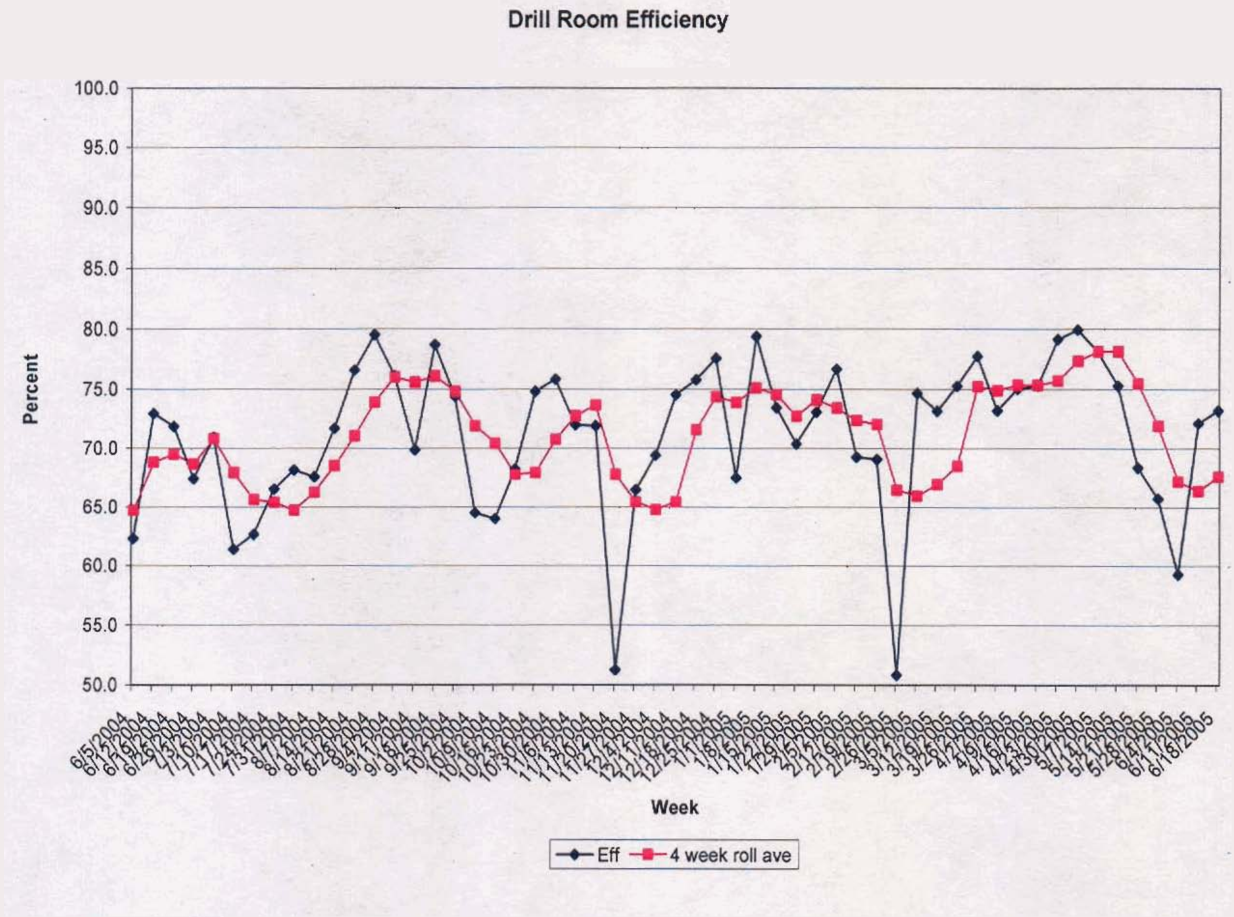



Figure 7: Drill Machine Utilization Trend

# Chapter V: Discussion

## Introduction

The researcher started this project with a goal of improving drill registration. Several quality tools were utilized to determine the best method to accomplish this goal. First, a review of existing business data was completed to determine the metric to monitor improvement. Selecting the correct metrics to monitor process improvement is vital since it will ultimately determine the success of the project. When presenting results to management is important to have data supporting your position. A review of existing equipment manufacturers provided a list of three available options. The machines were reviewed for based on several key features. After analyzing different features of each system, the system from Fein Focus was chosen. The build time for this equipment was nine months which provided time for other critical planning before arrival. A floor plan was completed to locate the system within the facility. Part of implementation consisted of defining x-ray target locations in a fixed location on the panels that conformed with the Fein Focus' requirements without losing available panel space. Then a drill tooling configuration was completed utilizing existing tooling schemes on the drill machines. It was cost prohibitive to develop a new drill tooling scheme due to the number of existing machines that would require modification. Upon machine arrival, a gage r & r was completed as part of the acceptance criteria. Once machine performance was accepted different targeting methods were evaluated with an ANOVA. Several factors influence the target acquisition method. Machine capacity and optimal drill registration weighed heavily into optimizing this process.

Conclusion

The researcher concludes that utilizing several quality techniques can lead to substantial process improvements. It is not possible to utilizing just one discipline to solve complex manufacturing problems. Experience in several disciplines is required to provide a complete solution. As the project develops it moves in sequential phases that require board experiences to ensure a successful implementation.

The drill optimizer has provided a 2% increase in machine utilization and has provided a reduction in internal shorts due to drill registration. But several other enterprise resources benefited from the implementation of the drill optimizer. The dry lab back log of 150 scale request dropped to zero. Previously, bad drill registration was not detectable to final process step. Manufacturing is now able to determine drill registration near the beginning of the operation and notify engineering when a problem is detected. When it is necessary to scrap a lot due to internal registration, it is preferable to do it near the start of the process as this provides better scheduling of customer shipments due to manufacturing lead time to restart a job that fails. Engineering previously spent several days to determine new layer scales, now it is a matter of hours. There are many different means to determine a successful implementation, but a comment like "I couldn't imagine not having the optimizer" signifies a successful project.

References

Craver, Robert H. (2004). *Doing Data Analysis with Minitab 14*. Toronto, Ontario, Canada: Brooks/Cole.

Interconnection Technology Research Institute, (1999). *A White Paper on Domestic PWB Technology Hurdles and Barriers, and a Strategy to Overcome Those Obstacles.*

Juran, J. M. (1974). *Quality Control Handbook* (3rd ed.). New York: McGraw-Hill

Kappele, William and Raffaldi, John. (2005, April). *Select the right Gage R&R Calculation Method*, Quality 38-41.

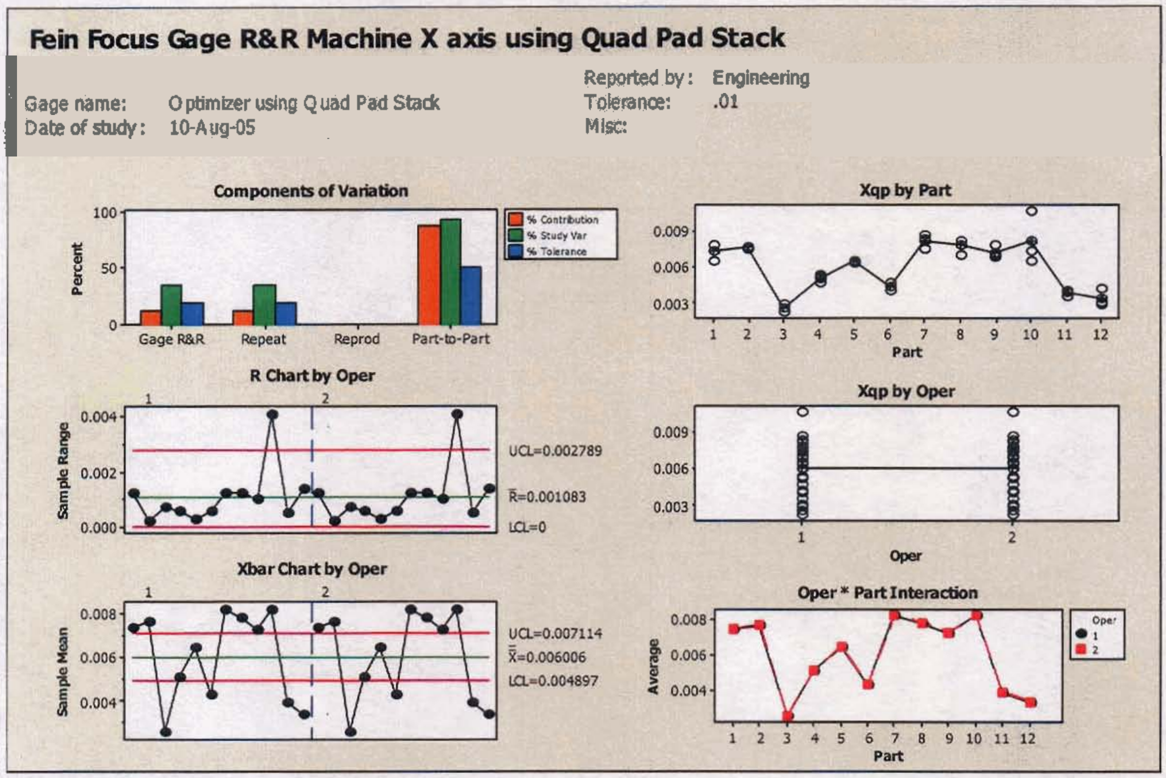
Montgomery, Douglas C. (1996). *Design and Analysis of Experiments* (4th ed.). New York: John Wiley & Sons.

Pyzdek, Thomas. (1999). *Quality Engineering Handbook*. New York, New York: Marcel Dekker.

Scarlett, J.A. (1985). *The Multilayer Printed Circuit Board Handbook*. Ayr, Scotland: Electrochemical Publications Limited

Yu, Lian, Shih, Heloisa M., Pfund, Michele, Carlyle, W. Matthew, and Fowler, John W.. (2002). *Scheduling of unrelated parallel machines: an application to PWB manufacturing*. IIE Transactions 34, 921-931

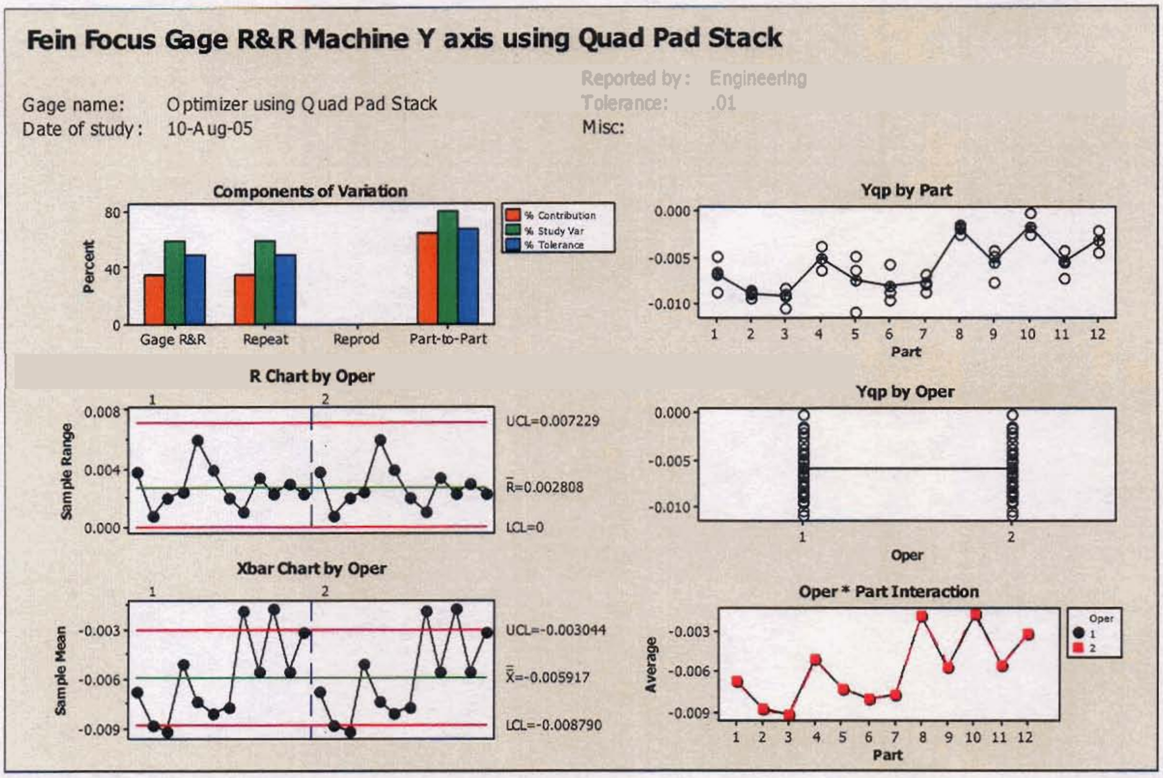
# Appendix A: Gage R&R using Quad Pad Stack




| Source | VarComp | %Contribution (of VarComp) |
|---|---|---|
| Total Gage R&R | 0.0000004 | 12.52 |
| Repeatability | 0.0000004 | 12.52 |
| Reproducibility | 0.0000000 | 0.00 |
| Part-To-Part | 0.0000029 | 87.48 |
| Total Variation | 0.0000033 | 100.00 |

| Source | StdDev (SD) | Study Var (6 * SD) | %Study Var (%SV) | %Tolerance (SV/Toler) |
|---|---|---|---|---|
| Total Gage R&R | 0.0006399 | 0.0038393 | 35.38 | 19.20 |
| Repeatability | 0.0006399 | 0.0038393 | 35.38 | 19.20 |
| Reproducibility | 0.0000000 | 0.0000000 | 0.00 | 0.00 |
| Part-To-Part | 0.0016915 | 0.0101493 | 93.53 | 50.75 |
| Total Variation | 0.0018085 | 0.0108512 | 100.00 | 54.26 |

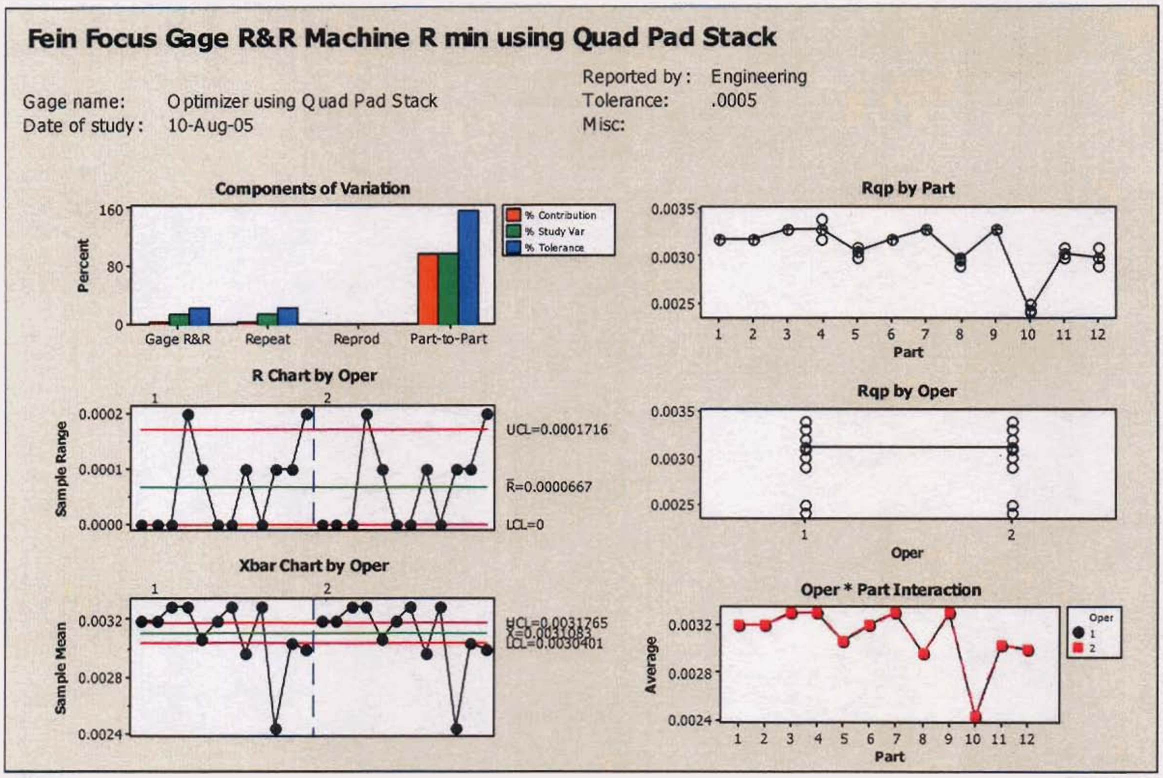
Number of Distinct Categories = 3




| Source | VarComp | %Contribution (of VarComp) |
|---|---|---|
| Total Gage R&R | 0.0000028 | 35.04 |
| Repeatability | 0.0000028 | 35.04 |
| Reproducibility | 0.0000000 | 0.00 |
| Part-To-Part | 0.0000051 | 64.96 |
| Total Variation | 0.0000079 | 100.00 |

| Source | StdDev (SD) | Study Var (6 * SD) | %Study Var (%SV) | %Tolerance (SV/Toler) |
|---|---|---|---|---|
| Total Gage R&R | 0.0016588 | 0.0099527 | 59.19 | 49.76 |
| Repeatability | 0.0016588 | 0.0099527 | 59.19 | 49.76 |
| Reproducibility | 0.0000000 | 0.0000000 | 0.00 | 0.00 |
| Part-To-Part | 0.0022587 | 0.0135522 | 80.60 | 67.76 |
| Total Variation | 0.0028024 | 0.0168143 | 100.00 | 84.07 |

Number of Distinct Categories = 1

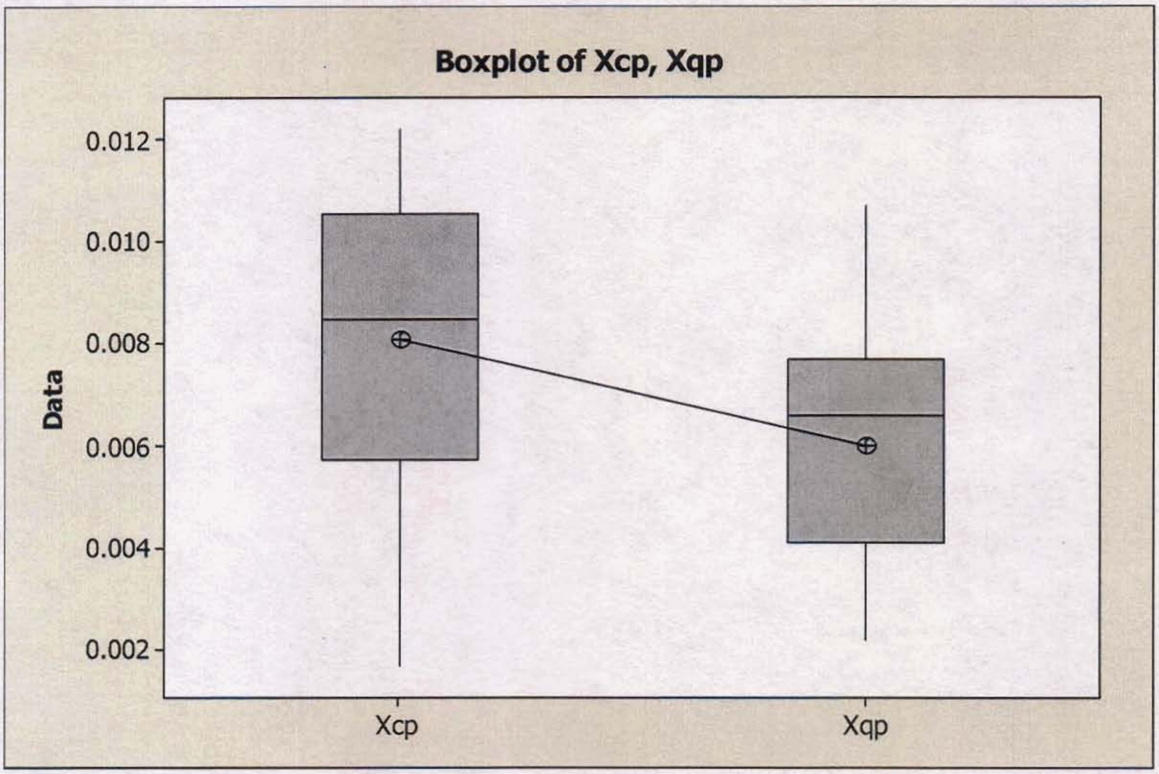



| Source | VarComp | %Contribution (of VarComp) |
|---|---|---|
| Total Gage R&R | 0.0000000 | 2.26 |
| Repeatability | 0.0000000 | 2.26 |
| Reproducibility | 0.0000000 | 0.00 |
| Part-To-Part | 0.0000001 | 97.74 |
| Total Variation | 0.0000001 | 100.00 |

| Source | StdDev (SD) | Study Var (6 * SD) | %Study Var (%SV) | %Tolerance (SV/Toler) |
|---|---|---|---|---|
| Total Gage R&R | 0.0000394 | 0.0002363 | 15.05 | 23.63 |
| Repeatability | 0.0000394 | 0.0002363 | 15.05 | 23.63 |
| Reproducibility | 0.0000000 | 0.0000000 | 0.00 | 0.00 |
| Part-To-Part | 0.0002587 | 0.0015522 | 98.86 | 155.22 |
| Total Variation | 0.0002617 | 0.0015701 | 100.00 | 157.01 |

Number of Distinct Categories = 9

# Appendix B: ANOVA Targeting Methods

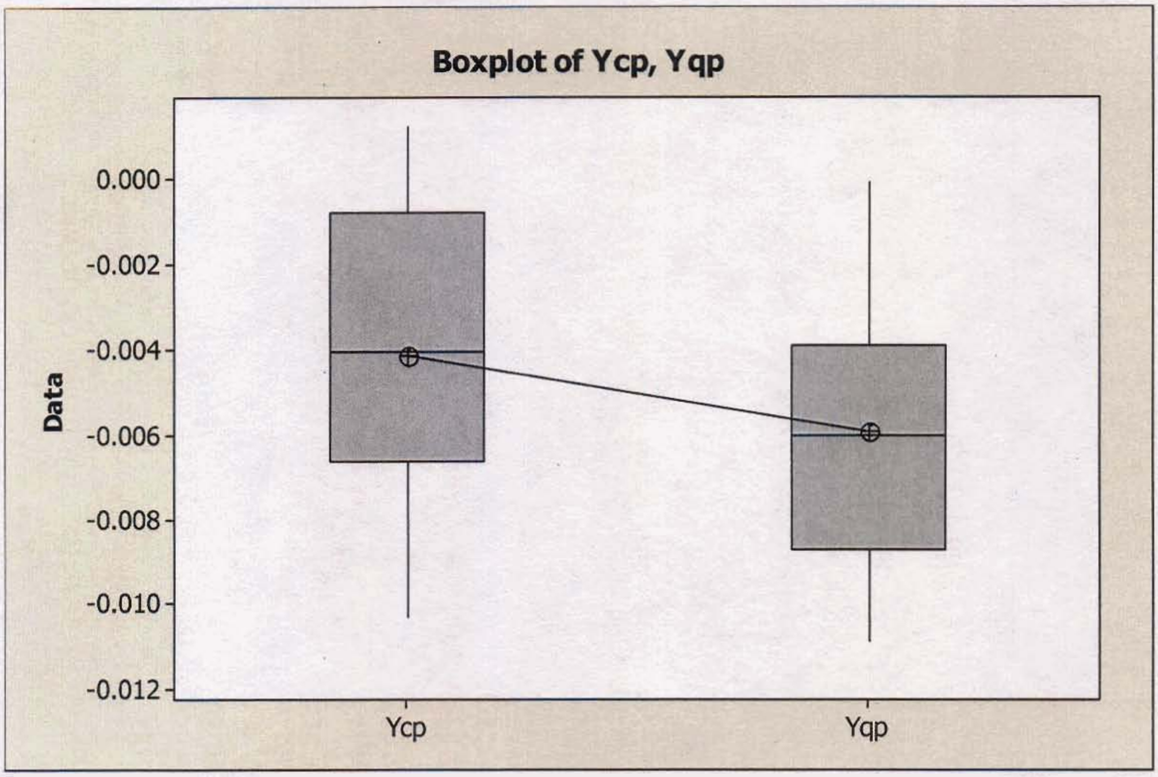



| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Factor | 1 | 0.0001546 | 0.0001546 | 23.89 | 0.000 |
| Error | 142 | 0.0009190 | 0.0000065 | | |
| Total | 143 | 0.0010736 | | | |

S = 0.002544 R-Sq = 14.40% R-Sq(adj) = 13.80%

```
                                Individual 95% CIs For Mean Based on
                                Pooled StDev
Level  N     Mean     StDev     ------+---------+---------+---------+---
Xcp   72  0.008078  0.002930                         (-----*-----)
Xqp   72  0.006006  0.002087    (-----*-----)
                                ------+---------+---------+---------+---
                                0.0060    0.0070    0.0080    0.0090
```

Pooled StDev = 0.00254

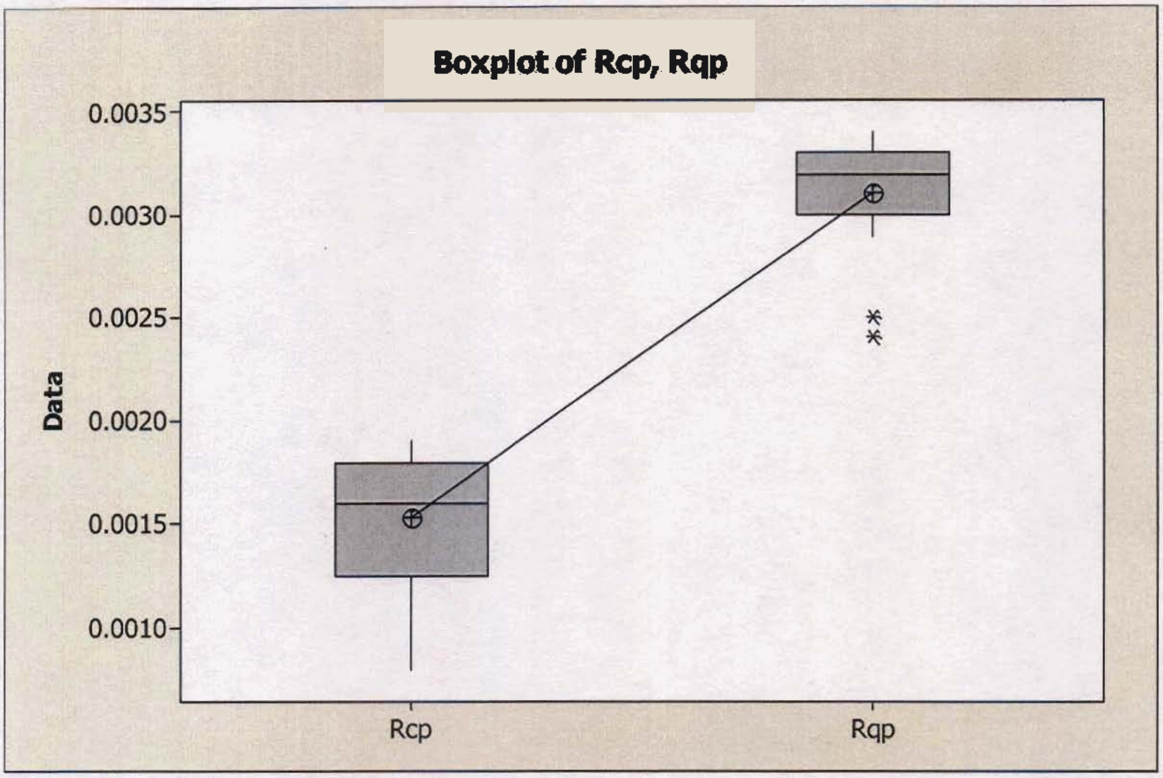



| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Factor | 1 | 0.0001166 | 0.0001166 | 12.34 | 0.001 |
| Error | 142 | 0.0013418 | 0.0000094 | | |
| Total | 143 | 0.0014585 | | | |

S = 0.003074   R-Sq = 8.00%   R-Sq(adj) = 7.35%

```
                             Individual 95% CIs For Mean Based on
                             Pooled StDev
Level   N      Mean     StDev   ------+---------+---------+---------+---
Ycp    72  -0.004117  0.003307                 (------*------)
Yqp    72  -0.005917  0.002822  (------*------)
                                ------+---------+---------+---------+---
                                 -0.0060   -0.0050   -0.0040   -0.0030
```

Pooled StDev = 0.003074



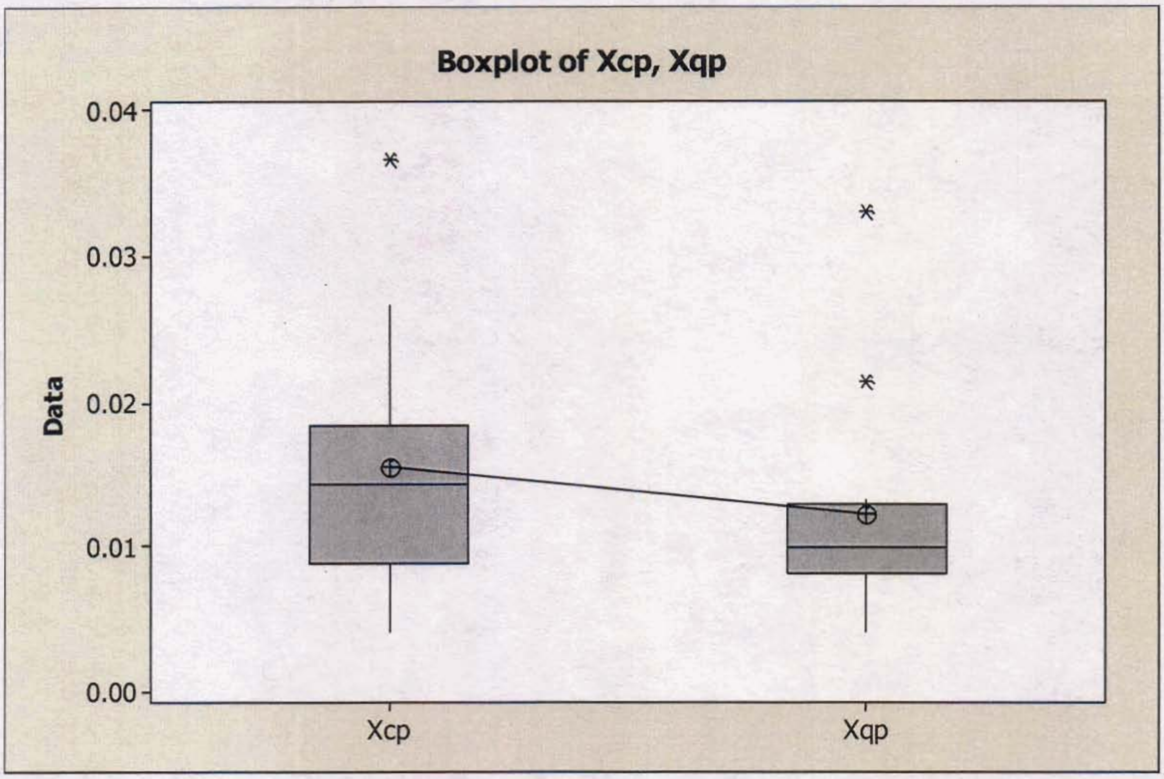

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Factor | 1 | 0.0000893 | 0.0000893 | 1163.92 | 0.000 |
| Error | 142 | 0.0000109 | 0.0000001 | | |
| Total | 143 | 0.0001002 | | | |

S = 0.0002770 R-Sq = 89.13% R-Sq(adj) = 89.05%

```
                              Individual 95% CIs For Mean Based on
                              Pooled StDev
Level   N      Mean     StDev     -+---------+---------+---------+--------
Rcp    72  0.0015333  0.0003086    (-*)
Rqp    72  0.0031083  0.0002413                                 (*)
                                  -+---------+---------+---------+--------
                                  0.00150   0.00200   0.00250   0.00300

Pooled StDev = 0.0002770
```

Appendix C: ANOVA Replication

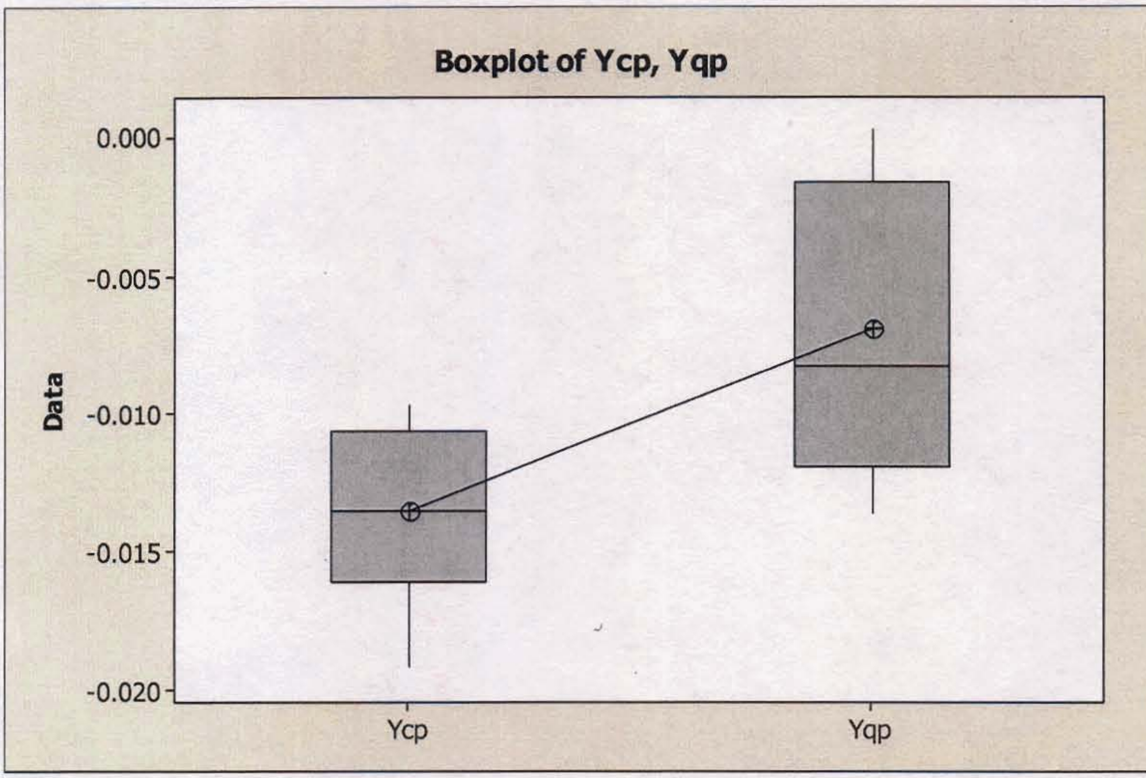



| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Factor | 1 | 0.0000618 | 0.0000618 | 0.89 | 0.357 |
| Error | 22 | 0.0015326 | 0.0000697 | | |
| Total | 23 | 0.0015944 | | | |

S = 0.008347 R-Sq = 3.87% R-Sq(adj) = 0.00%

```
                               Individual 95% CIs For Mean Based on Pooled
                               StDev
Level  N     Mean     StDev    ---------+---------+---------+---------+
Xcp   12  0.015567  0.008857            (------------*-------------)
Xqp   12  0.012358  0.007803   (------------*-------------)
                               ---------+---------+---------+---------+
                                     0.0105    0.0140    0.0175    0.0210
```

Pooled StDev = 0.008347

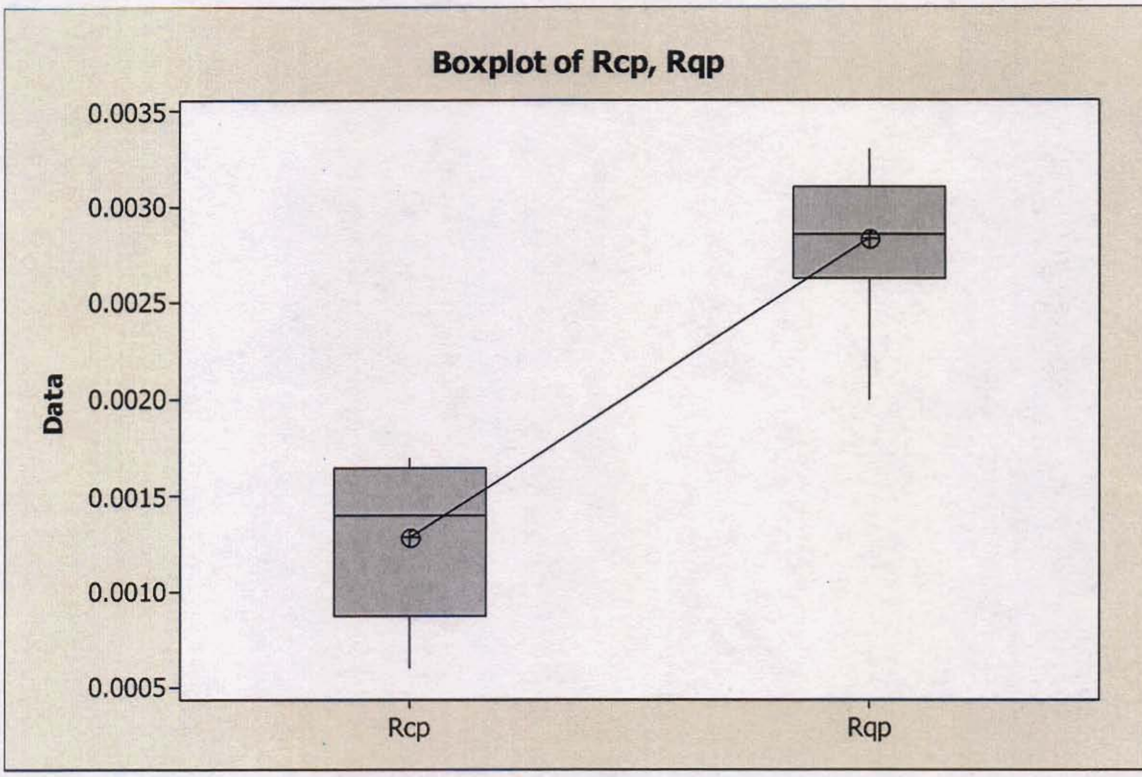



| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Factor | 1 | 0.0002647 | 0.0002647 | 15.01 | 0.001 |
| Error | 22 | 0.0003878 | 0.0000176 | | |
| Total | 23 | 0.0006525 | | | |

S = 0.004199   R-Sq = 40.56%   R-Sq(adj) = 37.86%

```
                        Individual 95% CIs For Mean Based on
                        Pooled StDev
Level  N      Mean    StDev    ---+---------+---------+---------+------
Ycp   12  -0.013525 0.003046   (-------*-------)
Yqp   12  -0.006883 0.005097                 (-------*-------)
                               ---+---------+---------+---------+------
                               -0.0150   -0.0120   -0.0090   -0.0060
```

Pooled StDev = 0.004199



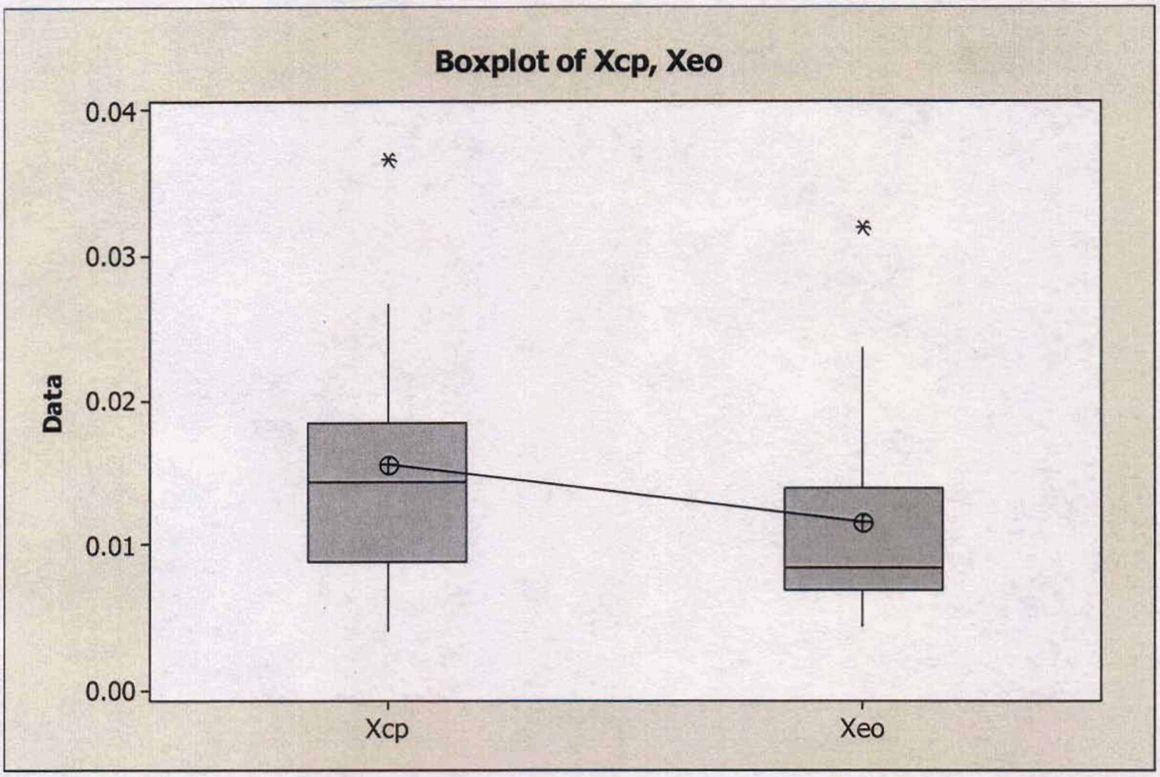

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Factor | 1 | 0.0000143 | 0.0000143 | 102.00 | 0.000 |
| Error | 22 | 0.0000031 | 0.0000001 | | |
| Total | 23 | 0.0000173 | | | |

S = 0.0003739 R-Sq = 82.26% R-Sq(adj) = 81.45%

| Level | N | Mean | StDev |
|---|---|---|---|
| Rcp | 12 | 0.0012917 | 0.0003825 |
| Rqp | 12 | 0.0028333 | 0.0003651 |

```
      Individual 95% CIs For Mean Based on Pooled StDev
Level  ---------+---------+---------+---------+
Rcp    (----*---)
Rqp                               (----*---)
       ---------+---------+---------+---------+
         0.00150   0.00200   0.00250   0.00300
```

Pooled StDev = 0.0003739

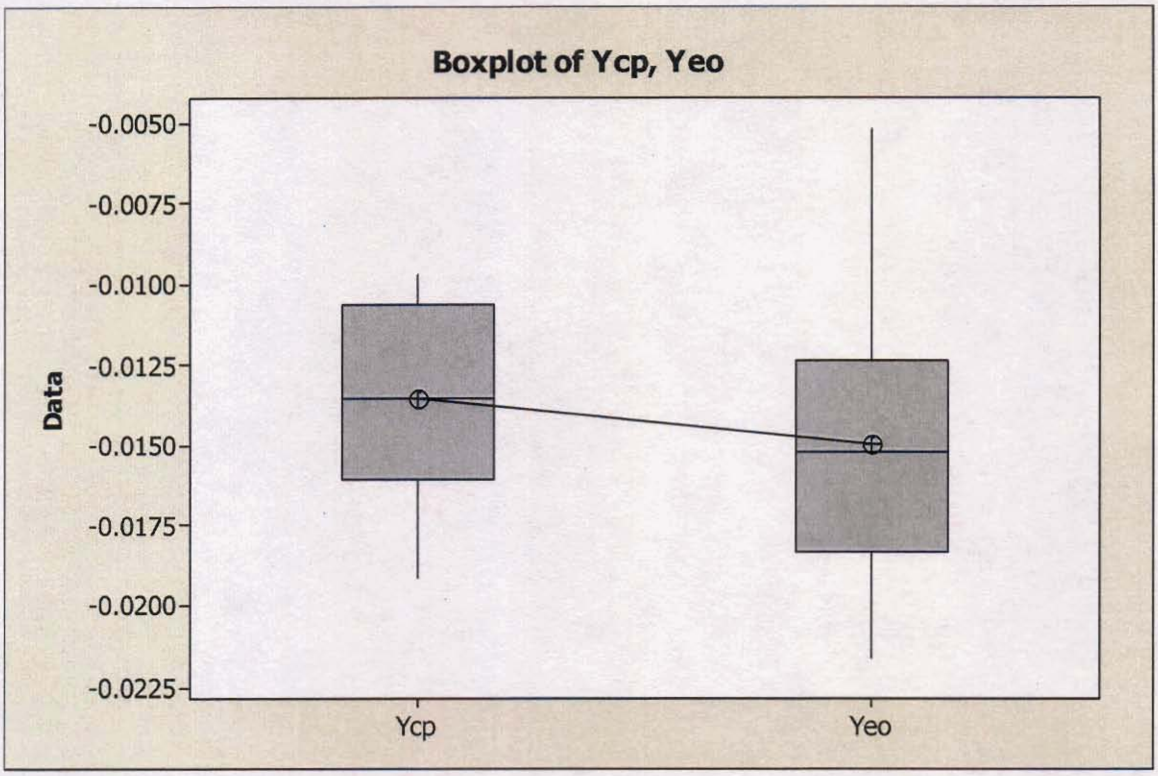



| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Factor | 1 | 0.0000932 | 0.0000932 | 1.28 | 0.271 |
| Error | 22 | 0.0016076 | 0.0000731 | | |
| Total | 23 | 0.0017008 | | | |

S = 0.008548   R-Sq = 5.48%   R-Sq(adj) = 1.18%

```
                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N      Mean     StDev    ----+---------+---------+---------+-----
Xcp    12  0.015567  0.008857            (-----------*-----------)
Xeo    12  0.011625  0.008228    (-----------*-----------)
                                 ----+---------+---------+---------+-----
                                 0.0080    0.0120    0.0160    0.0200
```

Pooled StDev = 0.008548

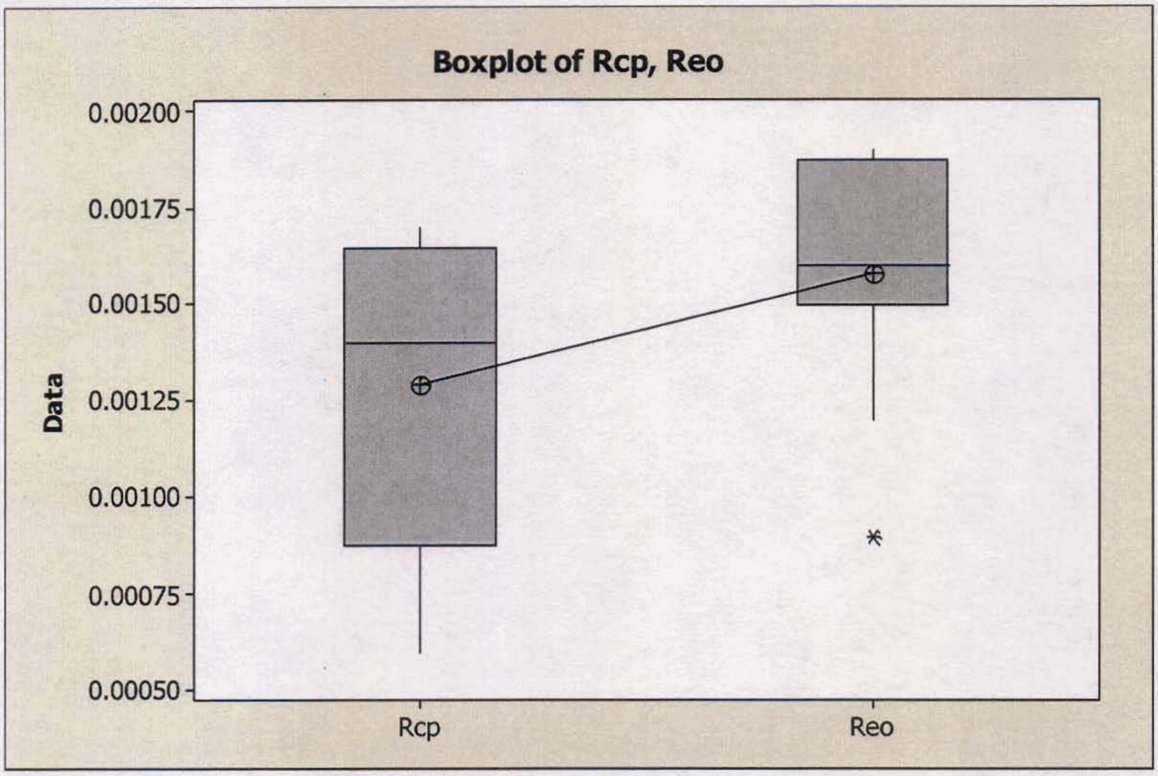



| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Factor | 1 | 0.0000119 | 0.0000119 | 0.82 | 0.374 |
| Error | 22 | 0.0003177 | 0.0000144 | | |
| Total | 23 | 0.0003296 | | | |

S = 0.003800   R-Sq = 3.61%   R-Sq(adj) = 0.00%

```
                       Individual 95% CIs For Mean Based on
                       Pooled StDev
Level   N       Mean     StDev   -----+---------+---------+---------+----
Ycp    12  -0.013525  0.003046               (--------------*--------------)
Yeo    12  -0.014933  0.004428       (--------------*--------------)
                                 -----+---------+---------+---------+----
                                 -0.0165   -0.0150   -0.0135   -0.0120
```

Pooled StDev = 0.003800




| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Factor | 1 | 0.0000005 | 0.0000005 | 4.28 | 0.051 |
| Error | 22 | 0.0000026 | 0.0000001 | | |
| Total | 23 | 0.0000031 | | | |

S = 0.0003455 R-Sq = 16.27% R-Sq(adj) = 12.47%

```
                              Individual 95% CIs For Mean Based on
                              Pooled StDev
Level   N      Mean     StDev     ------+---------+---------+---------+---
Rcp    12  0.0012917  0.0003825   (----------*---------)
Reo    12  0.0015833  0.0003040              (---------*----------)
                                  ------+---------+---------+---------+---
                                  0.00120   0.00140   0.00160   0.00180

Pooled StDev = 0.0003455
```

# Appendix D: Instantaneous Method $c_4$ Values

| Number of Trails | $c_4$ |
|---|---|
| 2 | 0.7979 |
| 3 | 0.8862 |
| 4 | 0.9213 |
| 5 | 0.9400 |
| 6 | 0.9515 |
| 7 | 0.9594 |
| 8 | 0.9650 |
| 9 | 0.9693 |
| 10 | 0.9727 |