

**ASSESSING MEASUREMENT SYSTEM ACCEPTABILITY FOR PROCESS
CONTROL AND ANALYSIS USING GAGE R&R STUDY**

By

Jiahong Wang

A Research Paper

**Submitted in Partial Fulfillment of the
Requirements for the
Master of Science Degree
In**

Management Technology

Approved: 3 Semester Credits

Dr. John Dzissah

**The Graduate School
University of Wisconsin-Stout**

May 2004

The Graduate School
University of Wisconsin Stout
Menomonie, WI 54751

ABSTRACT

	Wang	Jiahong	
(Writer)	(Last Name)	(First Name)	(Initial)
Assessing Measurement System Acceptability for Process Control and Analysis Using Gage R&R Study			
_____ (Title)			
Management Technology			
_____ (Graduate Major)			
John Dzissah		May 2004	106
(Research Advisor)		(Date)	(No. of Pages)
Publication Manual of the American Psychological Association (APA)			
_____ (Name of Style Manual Used in this Study)			

Gage R&R, which stands for gage repeatability and reproducibility, is a statistical tool that is applied to measure the amount of variation in the measurement system which arises from the people taking the measurement and the measurement device. The purpose of conducting the GR&R is to quantify measurement error and to reduce

the measurement system variation if it is excessive. In a typical gage R&R study, several operators each measure a selected set of items more than once.

This study is pursued in a large-scale manufacturing plant in western Wisconsin in order to evaluate the capability of a set of new measurement equipment that is just purchased by the company. Some potential problems related to the measurement system might be exposed after this study and recommendations would be made in order to achieve a successful quality improvement.

ACKNOWLEDGEMENTS

My sincere thanks you to, John Dzissah, my research director. John gave me professional direction as well as his time to help me complete this study.

In addition, a deep thanks to Michelle Stewart, the Quality Manager at the recreational vehicle manufacturing plant, who provided not only all the relevant data but also opportunities for me to visit and research their plant.

TABLE OF CONTENTS

	Page
Abstract	ii
Acknowledgements	iv
Table of Contents	v
List of Tables	vii
List of Figures	vii
 CHAPTER ONE: INTRODUCTION	
Statement of the study	1
Needs for the study	2
Objectives	2
Significance of the study	2
Limitations of the study	2
Definitions	2
 CHAPTER TWO: LITERATURE REVIEW	
Introduction	4
Measurement system error	4
Measurement process variation	5
Location variation	5
Width variation	8
Concept of gage R&R	10
Methods in gage R&R	12

Average and Range method	12
ANOVA method	14
Evaluation of results	14
CHAPTER THREE: METHODOLOGY	
Subjects	16
Instrumentation	16
Method for data collection	16
Data analysis.....	17
CHAPTER FOUR: REPORT OF FINDINGS	
Results	18
Summary of findings.....	18
Data analysis tables	22
CHAPTER FIVE: CONCLUTIONS AND RECOMMENDATIONS	
Statement of the problem	28
Method and procedures	28
Conclusions	28
Recommendations	29
REFERENCE	31
APPENDIX (a).....	32
APPENDIX (b).....	46
APPENDIX (c).....	70
APPENDIX (d).....	84

List of Tables

Tables	Page
1. Gage R&R Report for CMM (Round)	22
2. Gage R&R Report for CMM (Square)	23
3. Gage R&R Report for FARO arm (Round)	24
4. Gage R&R Report for FARO arm (Square)	25
5. R&R comparison sheet for CMM (Round).....	26
6. R&R comparison sheet for CMM (Square).....	26
7. R&R comparison sheet for FARO arm (Round).....	27
8. R&R comparison sheet for FARO arm (Square)	27

List of Figures

Figures	Page
1. Precision and accuracy	5
2. Repeatability, Reproducibility, and R&R.....	11
3. Average & Range Method, ANOVA Method.....	13

CHAPTER ONE

Introduction

A successful quality improvement or statistical process control program needs good measurement systems. More than often, a measurement system is evaluated by performing a designed experiment known as a gauge repeatability and reproducibility (R&R) study. The point of the study is to measure the measurement error in measurement systems. In other words, an R&R study analyzes the variation of measurements of a gage (repeatability) and variation of measurement by operators (reproducibility). It is so important in today's quality control process for the reason that the goal of process control is reduction of variation in the process and ultimately the products. Studies of measurement variation are a waste of time and money unless they lead to action to reduce process variation and improve process control. Since you can't address something that cannot be measured precisely, the assessment of the gage becomes an early priority (Barrentine, 2002).

Statement of the study

The purpose of this study is to evaluate a measurement system for a recreational vehicle manufacturer in the mid-western United States. Data are retrieved from a set of experiments that are set up on the manufacturing site. This study started in the fall semester, 2003. The researcher observed the plant environment, assisted with the set-up of the experiments and discussed potential problems with the vehicle maker in order to develop the measuring system.

Needs for the study

This R&R study is specifically designed for the vehicle manufacturer who just purchased a series of new measurement equipment and needs to identify the capability of the measurement system in order to control the whole manufacturing system to produce high quality and safe vehicles.

Objectives

1. Design and set up a gage R&R study on the Mt 4, Vector measuring system, FARO arm, and the CMM using square tube and round tube.
2. Analyze the experimental data by using ANOVA method.
3. Assess the capability of the measurement system and make recommendations for improvement.

Significance of the study

That the vehicle manufacturing process is in control highly relies on the capability of the measurement system. A detailed and specific gage R&R study will be developed. This study is planned to identify and thus prevent quality issues that are due to an incapable measurement system. The gage R&R study is a necessary and efficient quality control tool for the vehicle maker.

Limitations of this study

This study is limited to the researcher's time and the work experience in the vehicle manufacturing plant.

Definitions

Measurement: "the assignment of numbers or values to material things to represent the relations among them with respect to particular properties." This definition

was first given by C. Eisenhart (1963). The process of assigning the numbers is defined as the measurement process, and the value assigned is defined as the measurement value (MSA, 1995).

Gage: any device used to obtain measurements; frequently used to refer specifically to the devices used on the shop floor; includes go/no-go devices (MSA, 1995).

Measurement system: the collection of operations, procedures, gages and other equipment, software, and personnel used to assign a number to the characteristic being measured; the complete process used to obtain measurements (MSA, 2002).

Master: A standard that is used as a reference in a calibration process. May also be termed as reference or calibration standard (MSA, 2002).

CHAPTER TWO

Literature Review

Introduction

This chapter will discuss the concept of measurement system variation as well as the concept of gage R&R (repeatability & reproducibility) study and methods of a GRR study. This chapter will conclude with a report of findings about the significance of Gage R&R study on process control.

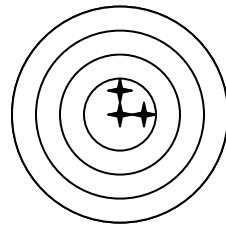
Measurement Systems Error

Typically, measurement system errors can be classified into two categories: accuracy and precision.

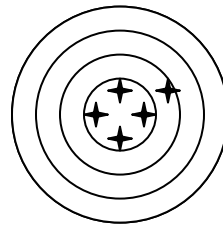
1. Accuracy describes the difference between the measurement and the part's actual value.
2. Precision describes the variation you see when you measure the same part repeatedly with the same device.

(MINITAB, 2000)

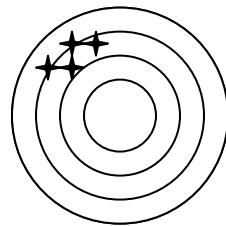
For any measurement system, there is always one or both of these problems in it. For instance, a device may measure parts precisely but not accurately; or a device is accurate but not precise, which means the measurements have large variance; or a device is neither accurate nor precise (figure 1).



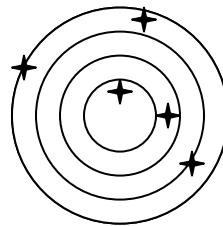
Accurate & precise



Accurate but not precise



Precise but not accurate



Not accurate or precise

Figure1: Precision and accuracy

Measurement Process Variation

The measurement system's variation can be characterized by location variation and width variation.

Location variation

The location variation shows how accurate the measurement system is.

Typically, it is broken into three components: *stability*, *bias/accuracy*, and *linearity*.

Stability is the total variation in the measurements obtained with a measurement system of the same master or parts when measuring a single characteristic over an extended time period. That is, stability is the change in bias over time (MSA, 2002).

Stability determination requires enough data sampled to cover a wide range of possible variation contributors that apply to the process being measured (Niles, 2003).

Instability can be caused by:

1. Worn equipment or instrument
2. Normal obsolescence or aging
3. Poor maintenance – power, hydraulic, corrosion, rust, power
4. Instrument needs to be calibrated/ reducing calibration interval
5. Poor quality instrument – conformance or design
6. Damaged or worn master, error in master
7. Instrument design or method is not robust
8. Different measurement method – loading, setup, technique
9. Distortion of gage or part
10. Environmental drift – humidity, vibration, temperature
11. Improper use of the setting master
12. Violation of an assumption, error in an applied constant
13. Improper application – position, part size, operator skill, observation error

(MSA, 2002)

Bias is the difference between the true value (reference value) and the observed average of measurements on the same characteristic on the same part (MSA, 2002). It is the measure of the systematic error of the measurement system. Bias is the contribution to the total error consisting of the combined effects of all sources of variation, known or unknown. The variations' contributions to the total error tend to offset predictably and consistently all results of repeated applications of the same measurement process at the measurement time period (MSA, 2002).

Excessive Bias can be resulted from:

1. Worn equipment, instrument or fixture

2. Equipment needs calibration
3. Damaged master/error in master
4. Poor quality instrument – conformance or design
5. Improper use of the setting master
6. Wrong gage for the application
7. Wrong Measuring characteristic
8. Linearity error
9. Distortion (part or gage)
10. Difference measurement method
11. Environmental drift – humidity, vibration, temperature
12. Improper use of the setting master
13. Violation of an assumption, error in an applied constant

(MSA, 2002)

Linearity is referred to as the difference of bias throughout the expected operating range of the equipment (MSA, 2002). A measurement process may have the capability of measuring small parts but much less accurate when measuring large parts or one end of a long part can be measured more accurately than the other end. It can be considered as a change of bias with respect to size.

If a measurement system has non-linearity, the possible causes can be:

1. Improper instrument calibration at both lower and upper end of the range
2. Damaged or worn instrument
3. Imprecise or inaccurate gage for application
4. Wrong instrument design characteristics

5. Environmental causes – humidity, vibration, or temperature

Width variation

The width variation shows how precise the measurement system is. Typically, it is broken into two components: *Repeatability* and *reproducibility*.

Repeatability is usually considered as the “with appraiser” variability. It is the measurement variation which is obtained with one measurement instrument used by one appraiser several times while measuring the identical characteristic on the same part (MSA, 2002). Usually, repeatability is regarded as equipment variation (EV), although this is not correct. In fact, repeatability is the common cause (random error) variation resulting from successive trials under defined and specific conditions of measurement. The correct term for repeatability is within-system variation when the condition of measurement are defined and fixed, (Fixed instrument, standard, operator, part, method, and assumptions and environment) (MSA, 2002). Two common sources of repeatability error are measurement variations due to the positional variation of the part in the instrument and instrument itself. The range chart is used to show the consistency of the measurement process because both of these variations are represented by the subgroup ranges of repeated measurements.

Besides the two common sources of repeatability errors, other possible errors include:

1. Within-instrument: wear, repair, fixture failure, poor maintenance or quality
2. Within-standard: class, wear or quality
3. Within-method: Variation in technique, setup, holding, zeroing, point density, or clamping

4. Within-part (sample): position, surface finish, form, sample consistency and taper
5. Within-environment: temperature, humidity, lighting, cleanliness and vibration
6. Within-appraiser: Position, experience, technique, fell, fatigue or training/
manipulation skill
7. Wrong gage for the application
8. Lack of rigidity (gage or part)
9. Violation of an assumption – proper operation or stable
10. Instrument design or method is not robust and uniform
11. Application – position, observation error or part size

(MSA, 2002)

Reproducibility is the “between appraisers” variability. Typically, it is defined as the variation in the average of the measurements which are made by different appraisers who use the same measuring instrument when measuring the same characteristic on the same part. This is often true when the manual instruments are influenced by the operators’ skill. However, it is not true when the measurement processes (i.e., automated systems) is used where the operator is not a significant source of variation. Because of this reason, reproducibility is considered as the average variation between-conditions or between systems of measurement (MINTAB, 2000)

Possible sources of reproducibility error in a measurement system include:

1. Between-instruments: average difference using instruments A, B, C, etc., for the same operators, parts and environment.
2. Between-parts: average difference when measuring types of parts A, B, C, etc., using the same instrument, method and operators.

3. Between-methods: average difference caused by changing point densities, zeroing, manual versus automated systems, clamping methods, or holding, etc.
4. Between-standards: average influence of different setting standards in the measurement process.
5. Between-appraisers: average difference between appraisers caused by technique, skill, training and experience. This is recommended study for process qualification and product and a manual instrument.
6. Between-environment: average difference in measurements over time caused by environmental cycles: this is the most common study for highly automated systems in product and process qualification
7. Instrument design or method is not robust
8. Assumption violation
9. Ineffective operator training
10. Application – position, observation error or part size

(MSA, 2002)

Concept of Gage R&R

“Gage refers to any device used for making measurements.” (Barrentine (2002).

An R&R study analyzes the variation of measurements of a gage (repeatability) and variation of measurement by operators (reproducibility). It plays a significant role in today’s quality control process for the reason that the goal of process control is to reduce variation in the process and the products. However, studies of measurement variation are a waste of time and money unless they lead to action to reduce process variation and improve process control. “Since you can’t address something that cannot

be measured precisely, the assessment of the gage becomes an early priority.” (Barrentine, 2002). “Gage R&R is an estimate of the combined variation of repeatability and reproducibility” (MSA, 2002) (figure 2). It amounts to the sum of between-system variances and within-system variances.

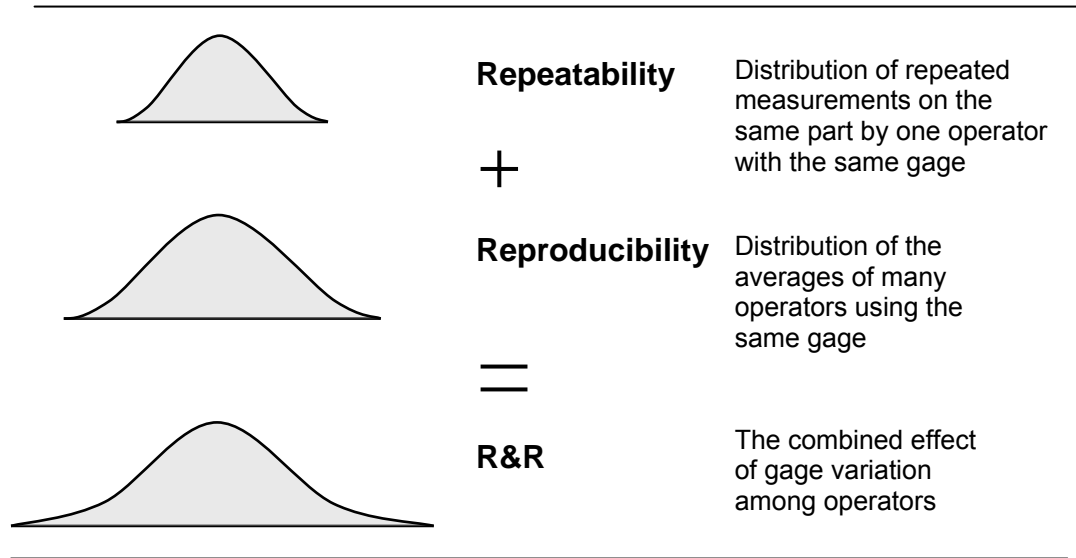


Figure 2 Repeatability, Reproducibility, and R&R (Barrentine, 2002)

The capacity of a measurement system simply includes the components of:

1. Repeatability and reproducibility (GR&R), including short-term consistency
2. Uncorrected bias or linearity

When the measurement errors are random and independent (uncorrelated), the capacity expression of combined variation can be quantified as:

$$\sigma^2_{\text{capacity}} = \sigma^2_{\text{bias (linearity)}} + \sigma^2_{\text{GRR}}$$

Methods in Gage R&R study

Gage R&R can be applied to any kind of measurements (attribute or variables, indeterminate or determinate). There are many methods overviewed in the literature that can be used to perform Gage R&R. A few of these methods are as follows:

1. Average and range method
2. Analysis of variance (ANOVA) method
3. Within part variation (WIV) method
4. Automotive Industry Action Group (AIAG, Southfield, MI) method
5. Short range method for destructive testing
6. Short range method for non-destructive testing
7. Long range method for destructive testing
8. Long range method for non-destructive testing
9. The Instantaneous method (one appraiser for equipment variation only) (Keller, 2003)

However, the two most common method types used and supported by statistical software are the ANOVA method (Analysis Of Variance) and the average and range method.

Average and Range Method

The Average and Range method (\bar{X} and R) is a mathematical method which provides estimates for variability caused by reproducibility and repeatability. This method allows the measurement systems to be broken down into three separate components: part-to-part, repeatability and reproducibility, but not their interaction. The

ANOVA method can be used to determine this interaction between the gage and appraisers (See figure3). However, both the Average and Range method and ANOVA method will provide information concerning the causes of measurement system or gage error.

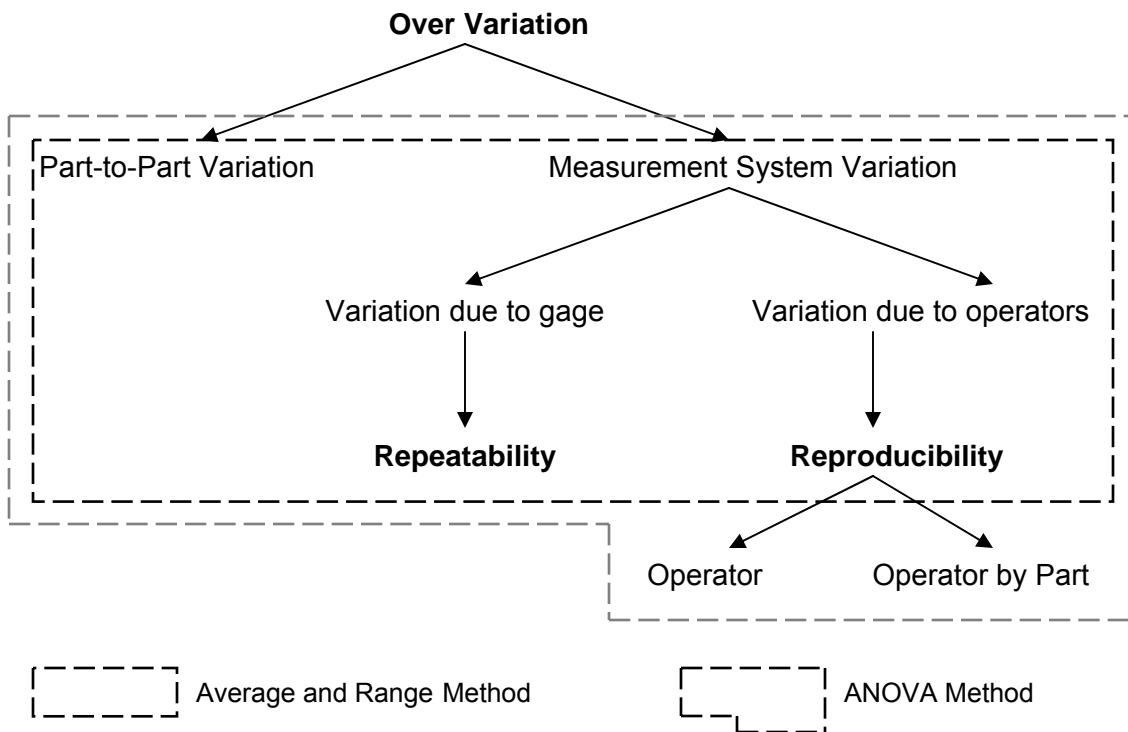


Figure 3: Average & Range Method, ANOVA Method

If reproducibility is large compared to repeatability, then possible causes could be:

- 1) The appraisers need to be better trained in how to use and read the gage instrument.

- 2) Calibrations on the gage dial are not correct.
- 3) A fixture of some sort may be needed to help the appraiser use the gage more consistently.

If repeatability is larger than reproducibility, the reasons may be:

- 1) The instrument needs to be well maintained.
- 2) The gage should be redesigned to be more rigid.
- 3) The location or clamping for gaging needs improvements.
- 4) There is excessive within-part variation.

(MSA, 1995)

ANOVA method

ANOVA is a standard statistical technique and can be used to analyze the measurement error and other sources of variability of data in a measurement systems study (MSA, 1995). In the analysis of variance, the variation can be broken down into four categories: parts, appraisers, interaction between parts and appraisers, and replication error due to the gage.

The advantages of ANOVA techniques as compared with Average and range methods are that ANOVA techniques have the capability to handle any experimental set-up, estimate the variances more precisely and accurately, can extract more information from the experimental data. The information includes interaction between parts and appraisers effect.

Evaluation of results

From a Gage study, %EV (the percent the repeatability or equipment variation), %AV (the percent the appraiser variation), %R&R (the percent the measurement

system variation for repeatability and reproducibility) and %PV (the percent the part-part variation) are calculated. Guidelines for acceptance of gage repeatability and reproducibility are:

1. Under 10% error – the measurement system is acceptable(satisfactory)
2. 10% to 30% error – the measurement system may be acceptable depending upon importance of application, cost of repairs or cost of gage, etc.,
3. Over 30% error – measurement system is not satisfactory. It needs improvement.

Problems need to be identified and corrected.

(MSA, 1995)

CHAPTER THREE

Methodology

Subjects:

The purpose of this study is to evaluate the capability of the measurement system that the manufacturing plant has recently applied in their production process.

Instrumentation:

The data collection sheets were developed by this researcher and adjusted by the plant personnel according to the real measuring environment. Both FARO Arm machine and CMM machine were used to measure the experimental parts.

Methods for data collection:

For each measurement machine, three appraisers were used to measure ten square parts and ten round parts. Each appraiser had to measure the same part three times. Each round part had seven dimensional characteristics and each square part had twelve dimensional characteristics.

To minimize the likelihood of misleading results, the following steps were taken.

1. The sample parts were selected from the process and had to represent its entire operating range.
2. The measurements were made in a random order.
3. The appraisers were unaware of which numbered part was being checked in order to avoid any possible knowledge bias.
4. Each appraiser used the same procedure, including all steps, to obtain the readings.

Data analysis

The numerical data that was retrieved by the appraisers has been input to MINITAB13 software for data analysis. MINITAB is a comprehensive statistical and graphical analysis software package and it has been providing statistical software solutions for over 25 years. Currently, MINITAB is used by thousands of companies worldwide, including GE, 3M, Ford Motor Company, and the leading Six Sigma consultants.

CHAPTER FOUR

Report of Findings

All the data has been analyzed through MINTAB 13 software. The capabilities of the two measuring machines (CMM & FARO Arm) are to measure both round and square parts. These have been revealed in the data result sheets. Therefore, they could be applied to boost the quality control system in this plant to produce safe and quality products.

Results

The data collection sheet and the original data results can be reviewed in the appendix at the end of the report.

Summary of Findings

The data results have been categorized in each of the following eight tables. Please see table 1 through table 8. Key numbers have been highlighted from the original data results in order to clarify the results. After reviewing the results of this study, it has been determined that the current measurement system is not adequate enough to conduct the necessary daily measuring tasks.

The following Gage R&R data result for CMM machine on the dimensional Characteristic with target value of 6.06 is used as a sample to explain some key result numbers.

Gage R&R for 6.06

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0022591	0.0002510	8.1722	0.00009
Operator	2	0.0020687	0.0010343	33.6758	0.00000
Operator*Part	18	0.0005529	0.0000307	0.5337	0.93012
Repeatability	60	0.0034533	0.0000576		



Total 89 0.0083340

Two-Way ANOVA Table Without Interaction

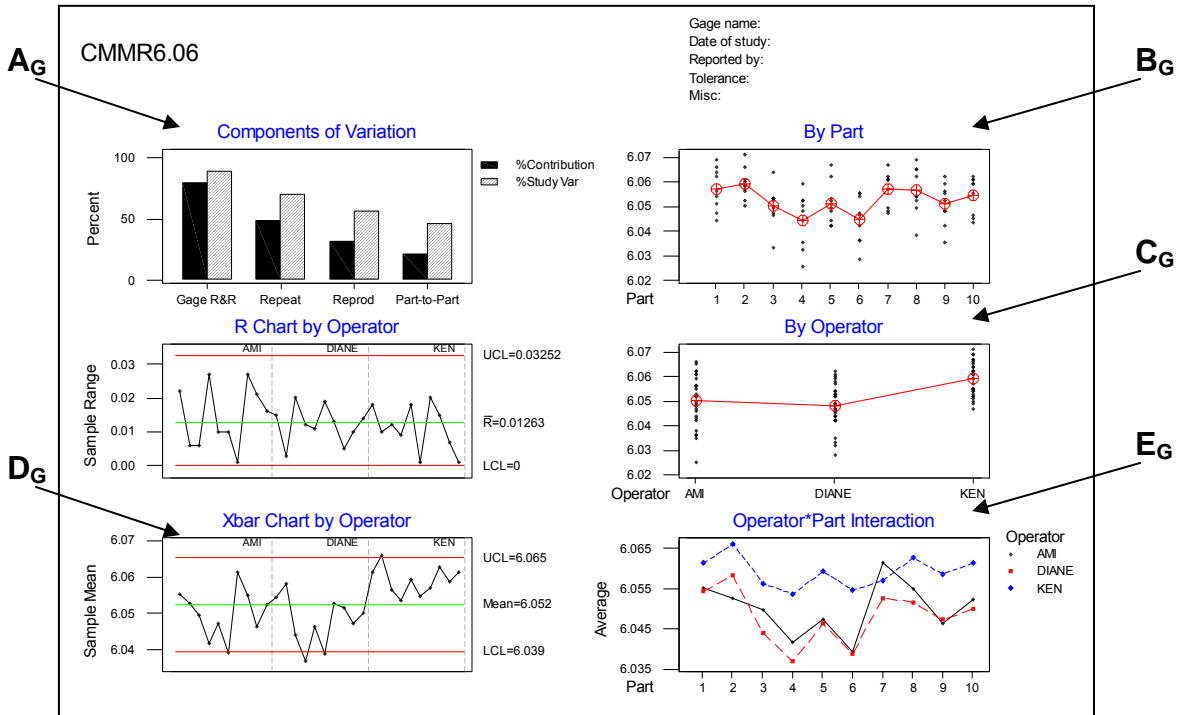
Source	DF	SS	MS	F	P
Part	9	0.0022591	0.0002510	4.8871	0.00003
Operator	2	0.0020687	0.0010343	20.1385	0.00000
Repeatability	78	0.0040062	0.0000514		
Total	89	0.0083340			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	8.41E-05	79.13
Repeatability	5.14E-05	48.31
Reproducibility	3.28E-05	30.82
Operator	3.28E-05	30.82
Part-To-Part	2.22E-05	20.87
Total Variation	1.06E-04	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	9.17E-03	4.72E-02	88.96
Repeatability	7.17E-03	3.69E-02	69.51
Reproducibility	5.72E-03	2.95E-02	55.52
Operator	5.72E-03	2.95E-02	55.52
Part-To-Part	4.71E-03	2.43E-02	45.68
Total Variation	1.03E-02	5.31E-02	100.00

Number of Distinct Categories = 1



- A. When the p-value for “Operator by Part” is < 0.25 , MINITAB fits the full model. In this case, the ANOVA method will be more accurate than the Xbar and R method. If the value is >0.25 , MINITAB fits the model without the interaction and uses the reduced model to define Gage R&R statistics (MINITAB User’s Guide, 2000).
- B. If the percent contribution from Part-Part is larger than that of Total Gage R&R, it tells us that most of the variation is due to differences between parts; very little is due to measurement system error. If the percent contribution from Total gage R&R is larger than that of Part-To-Part, it means that most of the variation is due to the measuring system; very little is due to differences between parts (MINITAB User’s Guide, 2000).
- C. According to AIAG, number “5” represents an adequate measuring system. The lower the number is, the poorer the measurement system would be. A very low number tells us that the measurement system cannot distinguish differences between parts (MINITAB User’s Guide, 2000).
- A_G This graph visualizes the “B” part, which shows the percentage differences between Part-Part and Total Gage R&R (MINITAB User’s Guide, 2000).
- B_G If the graph represents an erratic line (a non-level line), it tells us there are large differences between Parts. If it is almost a level-line, it tells us there is little difference between parts (MINITAB User’s Guide, 2000).
- C_G If the graph represents a nearly level line; it tells us there are small differences between operators. If it is a level-line, it tells us there is little difference between operators (MINITAB User’s Guide, 2000).

D_G If most of the points in the Xbar chart are outside the control limits, indicating the variation is mainly caused by differences between parts. If most of the points in the Xbar are inside the control limits, indicating the variation is mainly due to the measurement system (MINITAB User's Guide, 2000).

E_G This graph is a visualization of the p-value for Oper*Part. If the value is <0.25, the shape of each line tends to follow the same pattern and all the lines are close to each other, which indicates a significant interaction between Part and Operator (MINITAB User's Guide, 2000).

CMM (Round)								
*DC	A	B	C	Components of Variation	By Part	By Operator	Xbar Chart by Operator	Operator *Part Interaction
6.06	0.93012 No interaction	79.13: 20.87 Due to measurement system error	1 Poor	Due to measurement system	Some differences	Small differences	No differences between operators	Insignificant
6.38	0.23274 Interaction	84.49: 15.51 Due to measurement system error	1 Poor	Due to measurement system	Some differences	Small differences	No differences between operators	Insignificant
4.94	0.00009 Interaction	38.12: 61.88 Due to both	2 Poor	Due to measurement system	Some differences	Small differences	No differences between operators	Insignificant
14.98	0.47268 No interaction	100.00: 0.00 Due to measurement system error	0 Poor	Due to measurement system	Some differences	Small differences	No differences between operators	Insignificant
6.63	0.01806 Interaction	19.96: 80.04 Due to parts' differences	3 Poor	Due to measurement system	Some differences	Small differences	No differences between operators	Insignificant
3.82	0.62742 No interaction	34.97: 65.03 Due to measurement system error	2 Poor	Due to measurement system	Some differences	Small differences	No differences between operators	Insignificant
29.96	0.50748 No interaction	8.26: 91.74 Due to parts' differences	5 Adequate	Due to Differences between parts	Large differences	Small differences	Due to Differences between parts	Significant

Table 1: Gage R&R Report for CMM (Round)

CMM (Square)								
*DC	A	B	C	Components of Variation	By Part	By Operator	Xbar Chart by Operator	Operator *Part Interaction
16.66	0.00000 Interaction	71.35: 28.65 Due to measurement system error	1 Poor	Due to measurement system	Some differences	Small differences	Due to Differences between parts	Insignificant
22.68	0.00000 Interaction	55.24: 44.76 Due to both	1 Poor	Due to both	Some differences	Small differences	Due to Differences between parts	Insignificant
1.63a	0.00000 Interaction	58.33: 41.67 Due to both	1 Poor	Due to both	Some differences	Small differences	Due to Differences between parts	Insignificant
25.44	0.49920 No interaction	97.33: 2.67 Due to measurement system error	0 Poor	Due to measurement system	Some differences	Small differences	Due to Differences between parts	Insignificant
1.00	0.00455 Interaction	20.40 79.60 Due to parts' differences	3 fine	Due to Differences between parts	Big differences	Small differences	Due to Differences between parts	significant
38.03	0.44177 No interaction	39.57: 60.43 Due to both	2 Poor	Due to Both	Some differences	Small differences	Due to both	Insignificant
40.34	0.30950 No interaction	5.07: 94.93 Due to parts' differences	6 Adequate	Due to Differences between parts	Large differences	Small differences	Due to Differences between parts	Significant
1.63b	0.00000 Interaction	80.67: 19.33 Due to measurement system error	1 Poor	Due to Differences between parts	Some differences	Small differences	Due to Differences between parts	Insignificant
2.91	0.03593 Interaction	11.64: 88.36 Due to parts' differences	4 Adequate	Due to Differences between parts	Large differences	Small differences	Due to Differences between parts	Significant
40.1	0.04431 Interaction	76.15: 23.85 Due to both	1 Poor	Due to Both	Some differences	Small differences	Due to both	Insignificant
145	0.58448 No Interaction	93.80: 6.20 Due to measurement system error	0 Poor	Due to measurement system	Some differences	Small differences	Due to both	Insignificant
13.78	0.01229 Interaction	62.38: 37.62 Due to both	1 Poor	Due to Both	Some differences	Small differences	Due to both	Insignificant

Table 2: Gage R&R Report for CMM (Square)

*Due to both: Due to measurement system error and parts' differences

FARO Arm (Round)								
*DC	A	B	C	Components of Variation	By Part	By Operator	Xbar Chart by Operator	Operator *Part Interaction
4.94	0.00065 Interaction	30.04: 69.96 Due to both	2 Poor	Due to both	Some differences	Small differences	Due to Differences between parts	significant
6.63	0.01627 Interaction	18.24: 81.76 Due to parts' differences	3 Fine	Due to Differences between parts	big differences	Small differences	Due to Differences between parts	significant
29.96	0.29209 No interaction	8.37: 91.63 Due to parts' differences	5 Adequate	Due to Differences between parts	Large differences	Small differences	Due to Differences between parts	Significant
3.82	0.47269 No interaction	100.00: 0.00 Due to measurement system error	0 Poor	Due to measurement system	Some differences	Small differences	No differences between operators	Insignificant
14.98	0.07371 Interaction	41.91: 58.09 Due to both	2 Poor	Due to both	Some differences	Small differences	Due to both	Insignificant
6.38	0.49904 No interaction	43.12: 56.88 Due to both	2 Poor	Due to both	Some differences	Small differences	Due to both	Insignificant
6.06	0.53097 No interaction	82.16: 17.84 Due to measurement system error	1 Poor	Due to measurement system	Some differences	Small differences	No differences between operators	Insignificant

Table 3: Gage R&R Report for FARO Arm (Round)

FARO Arm (Square)								
*DC	A	B	C	Components of Variation	By Part	By Operator	Xbar Chart by Operator	Operator *Part Interaction
16.66	0.00002 Interaction	93.79: 6.21 Due to measurement system error	0 Poor	Due to measurement system	Some differences	Small differences	Due to Differences between parts	Insignificant
22.68	0.00167 Interaction	46.32: 53.68 Due to both	2 Poor	Due to both	Some differences	Small differences	Due to both	Insignificant
1.63a	0.00000 Interaction	69.06: 30.94 Due to both	1 Poor	Due to both	Some differences	Small differences	Due to Differences between parts	insignificant
25.44	0.01423 Interaction	87.82: 12.18 Due to measurement system error	1 Poor	Due to measurement system	Some differences	Small differences	Due to both	Insignificant
38.03	0.23682 Interaction	48.92: 51.08 Due to both	1 Poor	Due to Both	Some differences	Small differences	Due to both	Insignificant
40.34	0.19404 Interaction	3.13: 96.87 Due to parts' differences	8 Adequate	Due to Differences between parts	Large differences	Small differences	Due to Differences between parts	Significant
1.63b	0.00000 Interaction	53.09 46.91 Due to both	1 Poor	Due to Differences between parts	Some differences	Small differences	Due to Differences between parts	Insignificant
1.00	0.25522 No interaction	8.11: 91.89 Due to parts' differences	5 Adequate	Due to Differences between parts	Large differences	Small differences	Due to Differences between parts	Significant
2.91	0.08407 Interaction	3.62 96.38 Due to parts' differences	7 Adequate	Due to Differences between parts	Large differences	Small differences	Due to Differences between parts	Significant
40.1	** Error ** No variation within part/operator subgroups; Execution aborted.							
145	0.02855 Interaction	87.98: 12.02 Due to measurement system error	1 Poor	Due to measurement system	Some differences	Small differences	Due to both	Insignificant
13.78	0.40928 No interaction	5.51: 94.49 Due to parts' differences	6 Adequate	Due to Differences between parts	Large differences	Small differences	Due to Differences between parts	Significant

Table 4: Gage R&R Report for FARO Arm (Square)

CMM (Round)				
*DC	Repeatability(%)	Reproducibility(%)	Total GR%R	
6.06	48.31	30.82	79.13	
6.38	39.22	45.27	84.49	
4.94	16.99	21.13	38.12	
14.98	100.00	0.00	100.00	
6.63	10.80	9.16	19.96	<30%
3.82	30.07	4.89	34.97	
29.96	4.10	4.16	8.26	<30%

Table 5: R&R comparison sheet for CMM (Round)

CMM (Square)				
*DC	Repeatability(%)	Reproducibility(%)	Total GR%R	
16.66	12.45	58.90	71.35	
22.68	7.99	47.25	55.24	
1.63a	17.65	40.68	58.33	
25.44	33.50	63.83	97.33	
1.00	8.09	12.31	20.4	<30%
38.03	31.32	8.24	39.57	
40.34	2.39	2.67	5.07	<30%
1.63b	12.06	68.61	80.67	
2.91	5.6	6.05	11.64	<30%
40.1	44.51	31.65	76.15	
145	83.45	10.34	93.8	
13.78	28.14	34.24	62.38	

Table 6: R&R comparison sheet for CMM (Square)

FARO Arm (Round)				
*DC	Repeatability(%)	Reproducibility(%)	Total GR%R	
4.94	17.36	12.67	30.04	
6.63	9.87	8.37	18.24	
29.96	2.57	5.80	8.37	<30%
3.82	100.00	0.00	100.00	
14.98	23.66	18.25	41.91	
6.38	14.79	28.33	43.12	
6.06	23.67	58.49	82.16	

Table 7: R&R comparison sheet for FARO Arm (Round)

FARO Arm (Square)				
*DC	Repeatability(%)	Reproducibility(%)	Total GR%R	
16.66	15.77	78.02	93.79	
22.68	26.17	20.15	46.32	
1.63a	13.04	56.02	69.06	
25.44	40.42	47.4	87.82	
38.03	27.59	21.34	48.92	
40.34	1.7	1.44	3.13	< 30%
1.63b	11.55	41.55	53.09	
1.00	7.08	1.03	8.11	< 30%
2.91	3	0.62	3.62	< 30%
40.1				
145	52.38	35.6	87.98	
13.78	5.13	0.37	5.51	< 30%

Table 8: R&R comparison sheet for FARO Arm (Square)

CHAPTER FIVE

Conclusions and Recommendations

Statement of the Problem

The study was designed to evaluate the capability of a measurement system for a recreational vehicle manufacturer in the mid-western United States in order to improve the quality of its products.

Methods and Procedures

The Gage R&R study used ANOVA method which estimates the variances more precisely and accurately than Average and Range Method. Two measuring devices, CMM and FARO arm have been evaluated through the study. Data results were retrieved from MINTAB 13 software and based on these results further analysis was achieved.

Conclusions

The data results indicated that the overall measurement system is not acceptable for its intended application.

For the CMM machine as shown on table 5 and table 6, only five target values out of 19 fall into the less-than-30% category which indicates the measurement system may be acceptable. For the FARO arm as shown on table 7 and table 8, it is the same that only five target values out of 19 fall into the less-than-30% category. This also can be proved from table 1 to table 4 in the category **C** which uses a “5” as a watershed to roughly indicate whether a measurement system is capable or not. Overall, only about a quarter of total target values is satisfying. Thus, both machines represent a poor capability for measuring tasks.

Further investigation reveals that the poor capability is resulted from both measuring device itself and operators who were involved in the measurement processes. As shown on table 5 to table 8, for the %GR&R of those target values which are far away from satisfaction, the proportion of EV (repeatability%) value and AV (Reproducibility%) value varies. Neither of measuring device itself and measuring process assumes a dominating influence on the overall poor capability. However, to some degree, the error from the measuring device itself could be due to improper set-up and poor training for operators, considering the whole measuring system is rather advanced, sophisticated and up-to-date and was purchased by the company before long.

Recommendations

A thorough understanding of measurement variation and the contribution is essential. It is important to clearly define the problems or issues. Historical flowchart of the measurement system and process should be reviewed to lead to discussion of known and unknown information on the measurement system itself and its interrelationship to the process. A Cause and Effect Diagram could be applied to give valuable information resulting in a solution or a partial solution.

If the possible major causes lied in the measurement system itself, it will become necessary to analyze and resolve those issues before working on the rest of the system. Sometimes the errors in the measurement system itself are overlooked. Doing that may cause loss of resources and time since the focus is made on the process, when the actual problems are due the measurement device.

It is magnificent from this study that improvement of operator training and usage of qualified operators are compulsory. As the measuring devices are partially manual instruments, the study indicates that operator is a significant source of variation.

The changes made in the measurement system and the process should be tested until they reach an appropriate solution.

REFERENCE

- Devor, E.R., Chang, T., & Sutherland, W.J. (1992) *Statistical Quality Design and Control*. New York: Macmillan Publishing Company
- Early, A.T., & Neagu, R. (1999). *ANOVA Models and Data Reduction: Application to GR&R Studies*. Retrieved November 10, 2003, from web.utk.edu/~asaqp/qpr/QPRC1999/papers/early_and_neagu.pdf
- Gage R&R. (n.d.). Retrieved November 6, 2003, from www.statlets.com/gage_randr.htm
- Measurement Systems Analysis Reference Manual, 2nd ed.*, (1995, February). Chrysler Corp., Ford Motor Corp., General Motors Corp.
- Measurement Systems Analysis Reference Manual, 3rd ed.*, (2002, March). Chrysler Corp., Ford Motor Corp., General Motors Corp.
- MINITAB User's Guide 2: Data analysis and Quality Tools* (2000). Minitab Inc.
- Niles, K. (2001). *Characterizing the Measurement Process*. Retrieved November 2, 2003, from <http://healthcare.isixsigma.com/library/content/c020527a.asp>
- Scutoski, H., & Sekar, C. (1998). *Introduction to Gage R&R Study*. Retrieved November 5, 2003, from www.swtest.org/swtw_library/1998proc/PDF/T1_Hank.PDF
- Steve, D. P. and Keith, R. E. (1997). Guidelines for Expressing the Uncertainty of Measurement Results Containing Uncorrected Bias, *NIST Journal of Research*, 102, No. 5.

APPENDIX (a)

Data Results for CMM (Round)

12/21/03 11:10:48 AM

Welcome to Minitab, press F1 for help.

Gage R&R Study - ANOVA Method

Gage R&R for 6.06

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0022591	0.0002510	8.1722	0.00009
Operator	2	0.0020687	0.0010343	33.6758	0.00000
Operator*Part	18	0.0005529	0.0000307	0.5337	0.93012
Repeatability	60	0.0034533	0.0000576		
Total	89	0.0083340			

Two-Way ANOVA Table Without Interaction

Source	DF	SS	MS	F	P
Part	9	0.0022591	0.0002510	4.8871	0.00003
Operator	2	0.0020687	0.0010343	20.1385	0.00000
Repeatability	78	0.0040062	0.0000514		
Total	89	0.0083340			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	8.41E-05	79.13
Repeatability	5.14E-05	48.31
Reproducibility	3.28E-05	30.82
Operator	3.28E-05	30.82
Part-To-Part	2.22E-05	20.87
Total Variation	1.06E-04	100.00

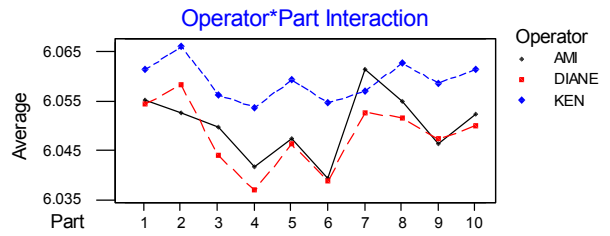
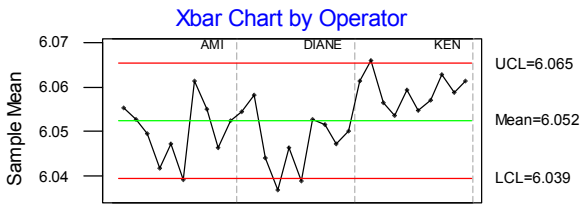
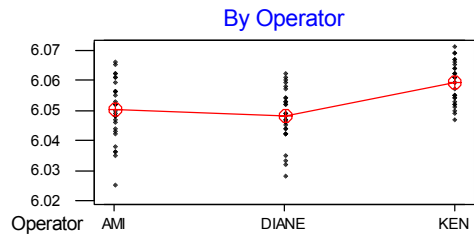
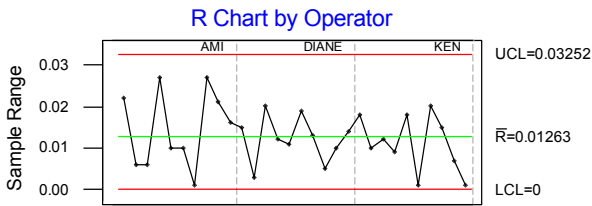
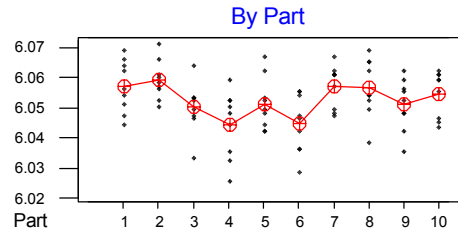
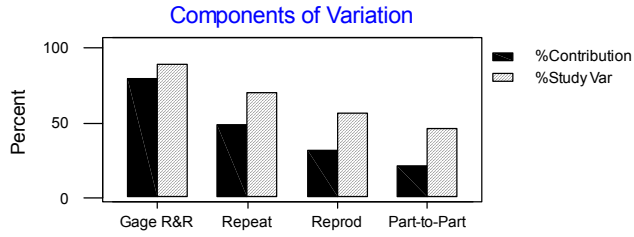
Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	9.17E-03	4.72E-02	88.96
Repeatability	7.17E-03	3.69E-02	69.51
Reproducibility	5.72E-03	2.95E-02	55.52
Operator	5.72E-03	2.95E-02	55.52
Part-To-Part	4.71E-03	2.43E-02	45.68
Total Variation	1.03E-02	5.31E-02	100.00

Number of Distinct Categories = 1

Gage R&R for 6.06

CMMR6.06

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:



Gage R&R Study - ANOVA Method

Gage R&R for 6.38

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0119429	0.0013270	3.7777	0.00790
Operator	2	0.0181473	0.0090736	25.8307	0.00001
Operator*Part	18	0.0063229	0.0003513	1.2813	0.23274
Repeatability	60	0.0164493	0.0002742		
Total	89	0.0528625			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	5.91E-04	84.49
Repeatability	2.74E-04	39.22
Reproducibility	3.16E-04	45.27
Operator	2.91E-04	41.59
Operator*Part	2.57E-05	3.68
Part-To-Part	1.08E-04	15.51
Total Variation	6.99E-04	100.00

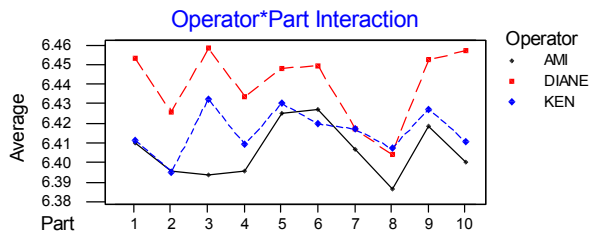
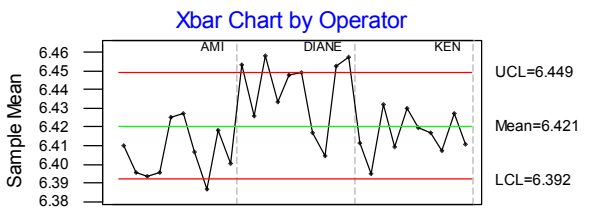
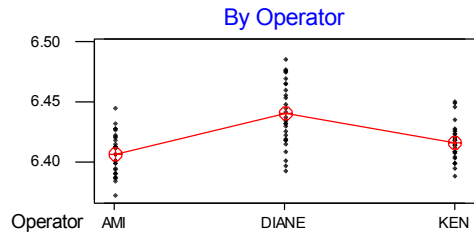
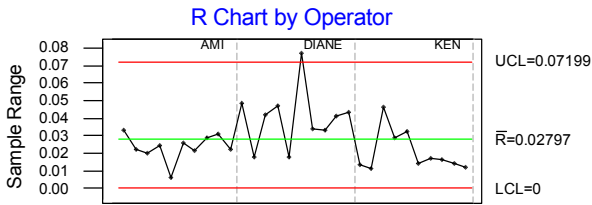
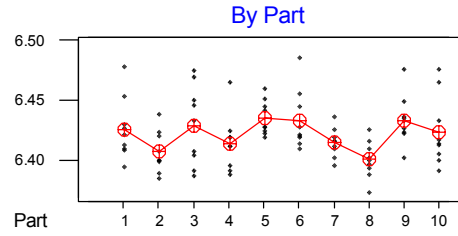
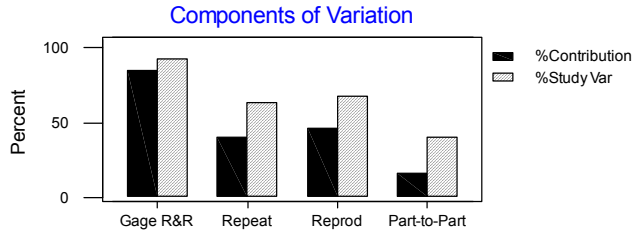
Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	2.43E-02	0.125157	91.92
Repeatability	1.66E-02	0.085272	62.63
Reproducibility	1.78E-02	0.091614	67.28
Operator	1.71E-02	0.087814	64.49
Operator*Part	5.07E-03	0.026111	19.18
Part-To-Part	1.04E-02	0.053623	39.38
Total Variation	2.64E-02	0.136161	100.00

Number of Distinct Categories = 1

Gage R&R for 6.38

CMMR6.38

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:



Gage R&R Study - ANOVA Method

Gage R&R for 4.94

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0018200	0.0002022	10.0565	0.00002
Operator	2	0.0001638	0.0000819	4.0734	0.03473
Operator*Part	18	0.0003620	0.0000201	3.6196	0.00009
Repeatability	60	0.0003333	0.0000056		
Total	89	0.0026791			

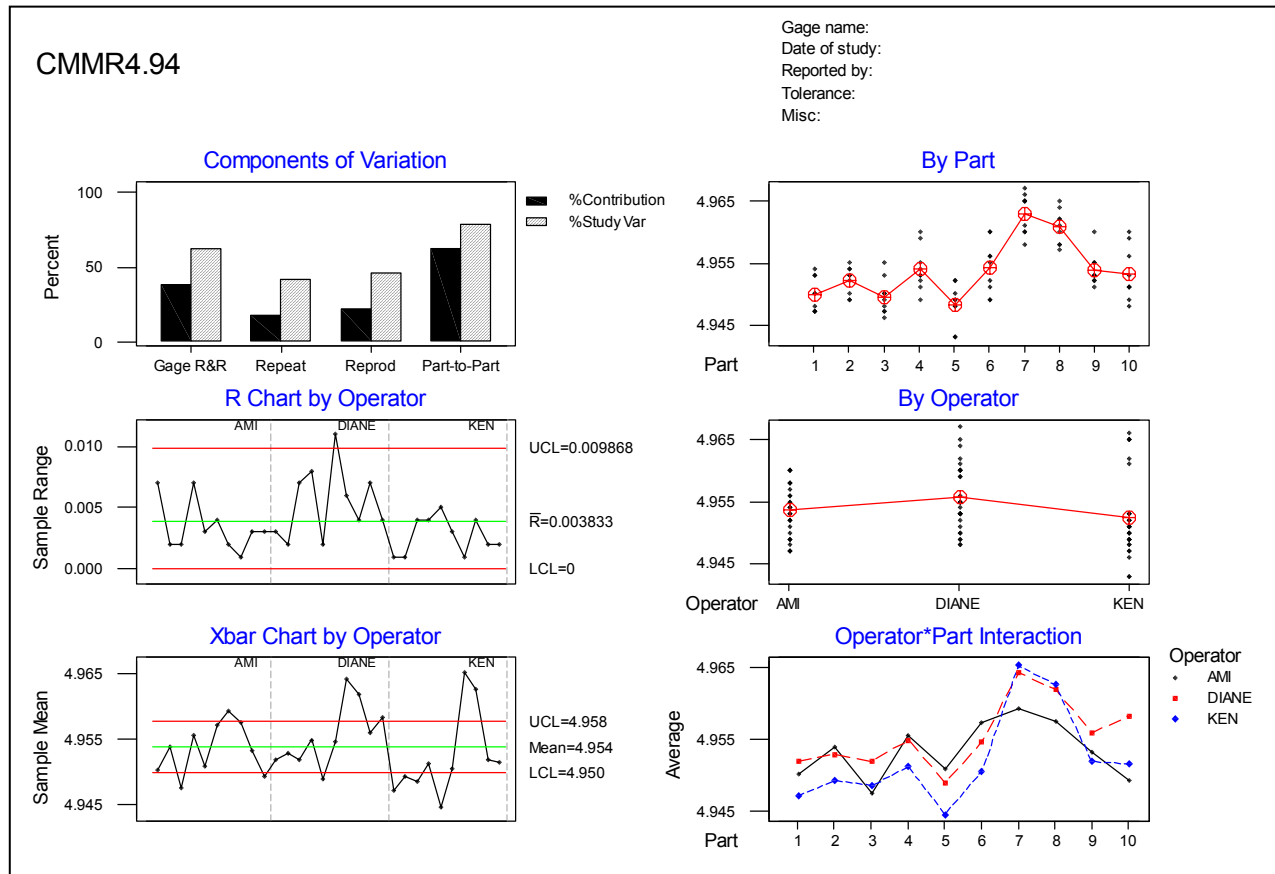
Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	1.25E-05	38.12
Repeatability	5.56E-06	16.99
Reproducibility	6.91E-06	21.13
Operator	2.06E-06	6.30
Operator*Part	4.85E-06	14.83
Part-To-Part	2.02E-05	61.88
Total Variation	3.27E-05	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	3.53E-03	1.82E-02	61.74
Repeatability	2.36E-03	1.21E-02	41.22
Reproducibility	2.63E-03	1.35E-02	45.97
Operator	1.44E-03	7.39E-03	25.10
Operator*Part	2.20E-03	1.13E-02	38.52
Part-To-Part	4.50E-03	2.32E-02	78.66
Total Variation	5.72E-03	2.95E-02	100.00

Number of Distinct Categories = 2

Gage R&R for 4.94



Gage R&R Study - ANOVA Method

Gage R&R for 14.98

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	22556750	2506306	0.99999	0.47416
Operator	2	5012365	2506182	0.99994	0.38744
Operator*Part	18	45113868	2506326	1.00000	0.47268
Repeatability	60	150379079	2506318		
Total	89	223062062			

Two-Way ANOVA Table Without Interaction

Source	DF	SS	MS	F	P
Part	9	22556750	2506306	0.99999	0.44731
Operator	2	5012365	2506182	0.99995	0.37257
Repeatability	78	195492947	2506320		
Total	89	223062062			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	2506320	100.00
Repeatability	2506320	100.00
Reproducibility	0	0.00
Operator	0	0.00
Part-To-Part	0	0.00
Total Variation	2506320	100.00

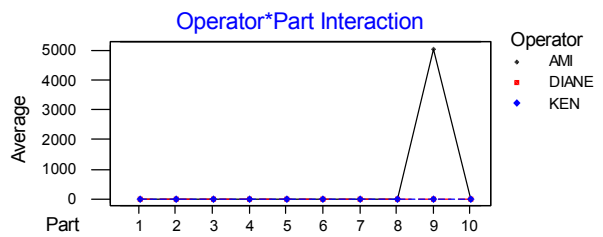
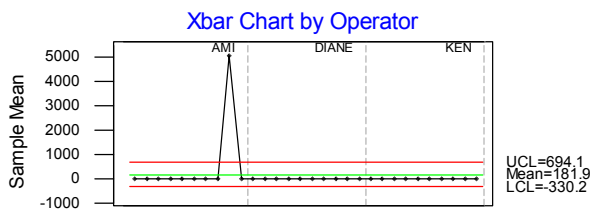
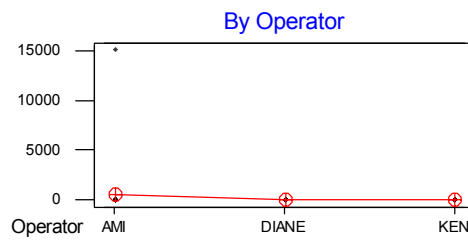
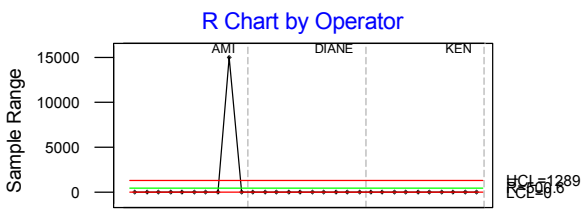
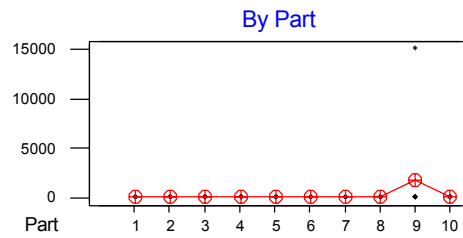
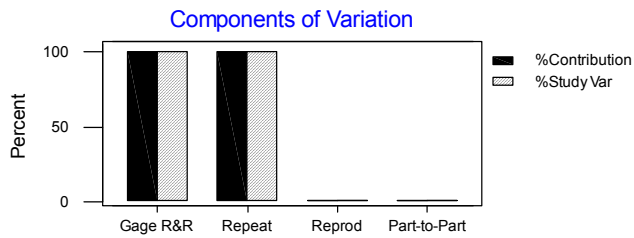
Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	1583.14	8153.15	100.00
Repeatability	1583.14	8153.15	100.00
Reproducibility	0.00	0.00	0.00
Operator	0.00	0.00	0.00
Part-To-Part	0.00	0.00	0.00
Total Variation	1583.14	8153.15	100.00

Number of Distinct Categories = 0

Gage R&R for 14.98

CMMR14.98

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:



Gage R&R Study - ANOVA Method

Gage R&R for 6.63

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0124945	0.0013883	33.0668	0.00000
Operator	2	0.0006756	0.0003378	8.0462	0.00319
Operator*Part	18	0.0007557	0.0000420	2.0796	0.01806
Repeatability	60	0.0012113	0.0000202		
Total	89	0.0151371			

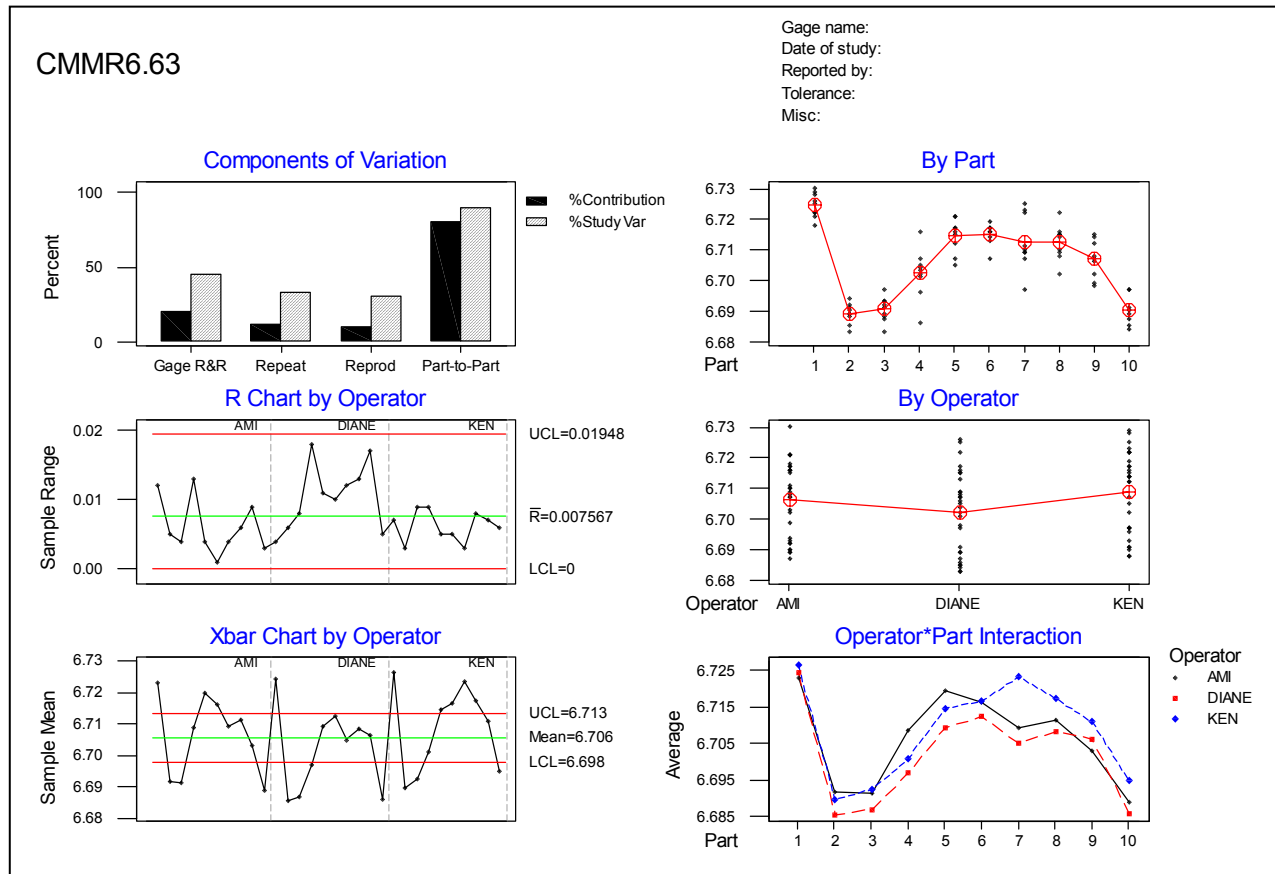
Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	3.73E-05	19.96
Repeatability	2.02E-05	10.80
Reproducibility	1.71E-05	9.16
Operator	9.86E-06	5.28
Operator*Part	7.27E-06	3.89
Part-To-Part	1.50E-04	80.04
Total Variation	1.87E-04	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	6.11E-03	3.15E-02	44.68
Repeatability	4.49E-03	2.31E-02	32.87
Reproducibility	4.14E-03	2.13E-02	30.27
Operator	3.14E-03	1.62E-02	22.97
Operator*Part	2.70E-03	1.39E-02	19.72
Part-To-Part	1.22E-02	6.30E-02	89.46
Total Variation	1.37E-02	7.04E-02	100.00

Number of Distinct Categories = 3

Gage R&R for 6.63



Gage R&R Study - ANOVA Method

Gage R&R for 3.82

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0252442	0.0028049	23.0632	0.00000
Operator	2	0.0016124	0.0008062	6.6290	0.00696
Operator*Part	18	0.0021891	0.0001216	0.8583	0.62742
Repeatability	60	0.0085020	0.0001417		
Total	89	0.0375478			

Two-Way ANOVA Table Without Interaction

Source	DF	SS	MS	F	P
Part	9	0.0252442	0.0028049	20.4640	0.00000
Operator	2	0.0016124	0.0008062	5.8819	0.00418
Repeatability	78	0.0106911	0.0001371		
Total	89	0.0375478			

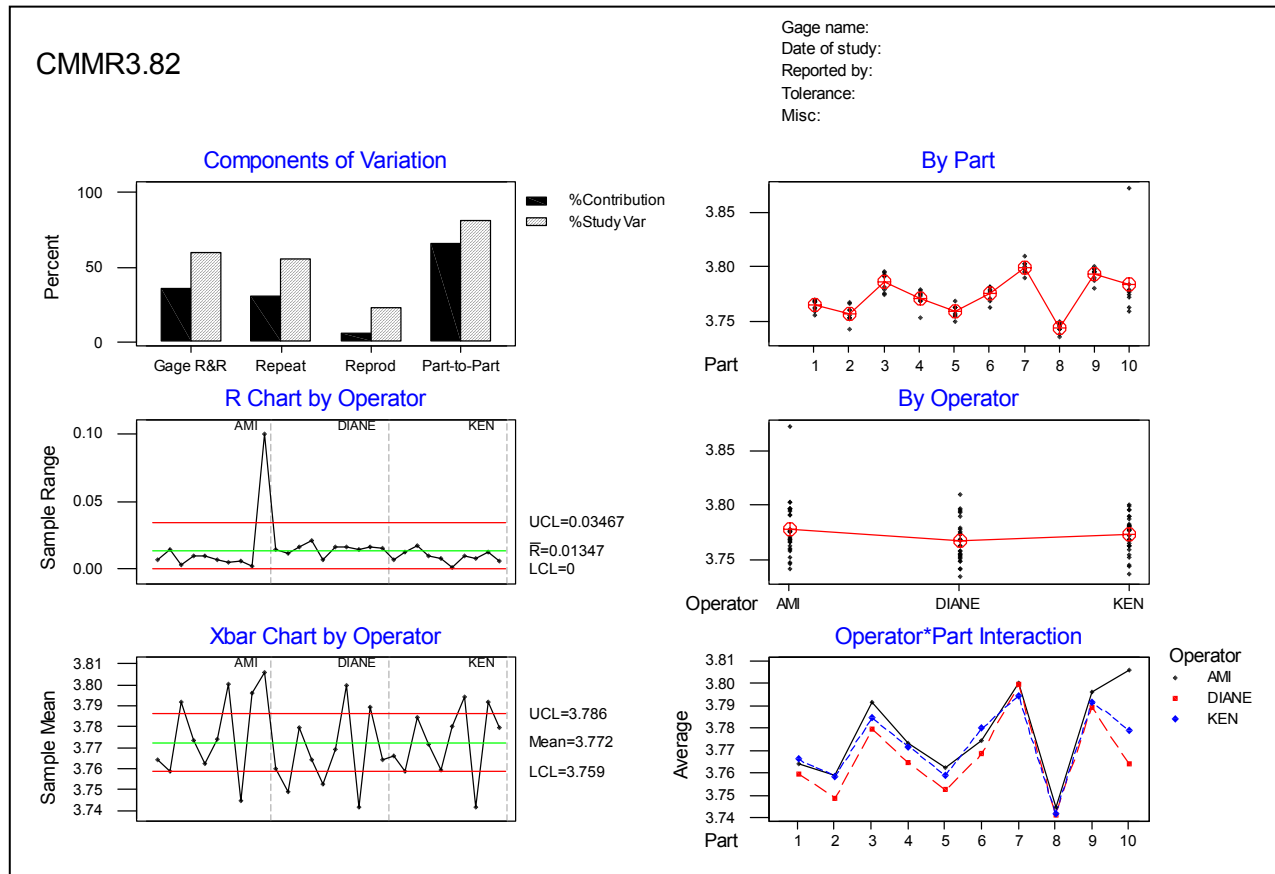
Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	1.59E-04	34.97
Repeatability	1.37E-04	30.07
Reproducibility	2.23E-05	4.89
Operator	2.23E-05	4.89
Part-To-Part	2.96E-04	65.03
Total Variation	4.56E-04	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	1.26E-02	0.065015	59.13
Repeatability	1.17E-02	0.060294	54.84
Reproducibility	4.72E-03	0.024322	22.12
Operator	4.72E-03	0.024322	22.12
Part-To-Part	1.72E-02	0.088668	80.64
Total Variation	2.13E-02	0.109950	100.00

Number of Distinct Categories = 2

Gage R&R for 3.82



Gage R&R Study - ANOVA Method

Gage R&R for 29.96

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0303293	0.0033699	207.703	0.00000
Operator	2	0.0010464	0.0005232	32.247	0.00000
Operator*Part	18	0.0002920	0.0000162	0.967	0.50748
Repeatability	60	0.0010067	0.0000168		
Total	89	0.0326744			

Two-Way ANOVA Table Without Interaction

Source	DF	SS	MS	F	P
Part	9	0.0303293	0.0033699	202.396	0.00000
Operator	2	0.0010464	0.0005232	31.423	0.00000
Repeatability	78	0.0012987	0.0000167		
Total	89	0.0326744			

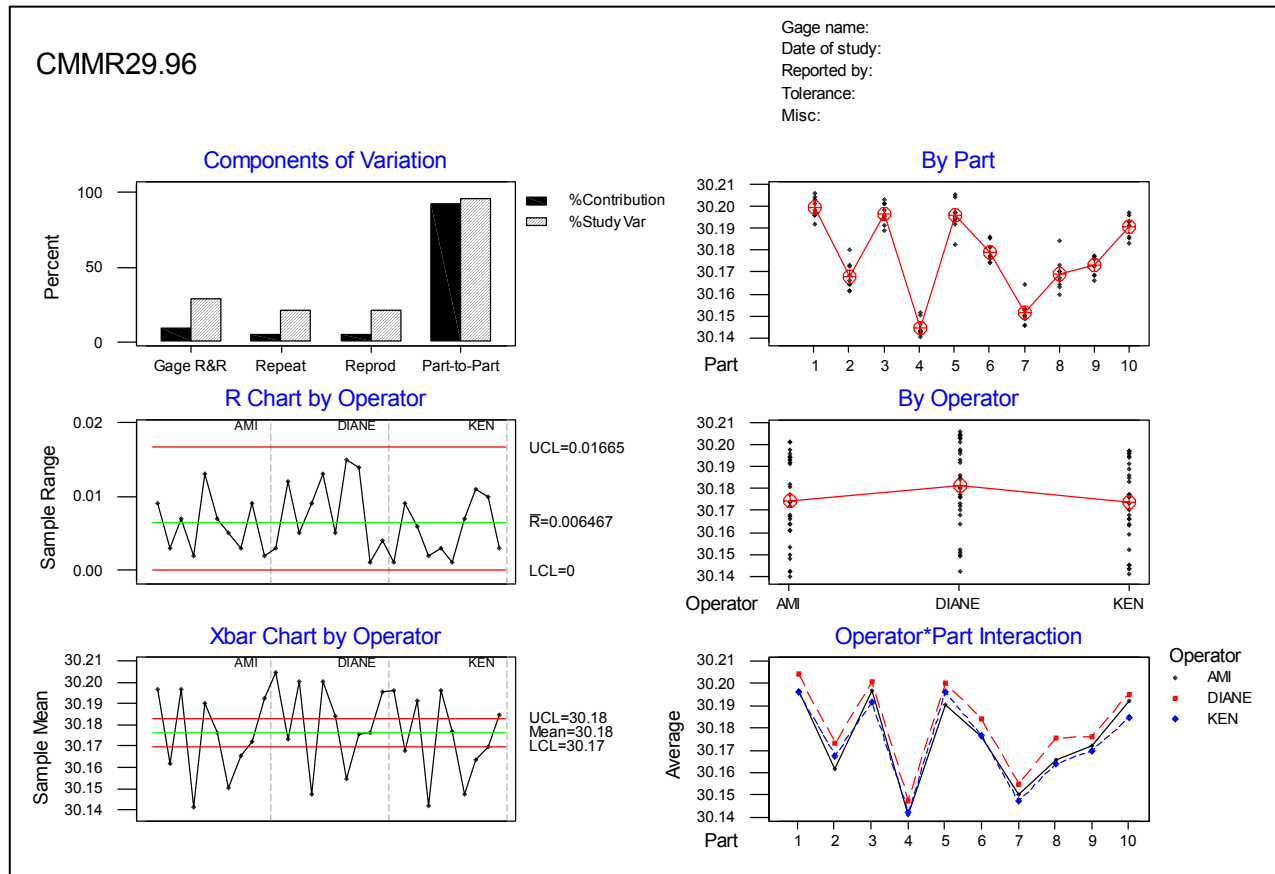
Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	3.35E-05	8.26
Repeatability	1.67E-05	4.10
Reproducibility	1.69E-05	4.16
Operator	1.69E-05	4.16
Part-To-Part	3.73E-04	91.74
Total Variation	4.06E-04	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	5.79E-03	0.029823	28.74
Repeatability	4.08E-03	0.021014	20.25
Reproducibility	4.11E-03	0.021162	20.39
Operator	4.11E-03	0.021162	20.39
Part-To-Part	1.93E-02	0.099408	95.78
Total Variation	2.02E-02	0.103785	100.00

Number of Distinct Categories = 5

Gage R&R for 29.96



APPENDIX (b)

Data results for CMM (Square)

12/21/03 11:18:28 AM

Welcome to Minitab, press F1 for help.

Gage R&R Study - ANOVA Method

Gage R&R for 16.66

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0160458	0.0017829	3.43072	0.01248
Operator	2	0.0091772	0.0045886	8.82968	0.00213
Operator*Part	18	0.0093542	0.0005197	8.52084	0.00000
Repeatability	60	0.0036593	0.0000610		
Total	89	0.0382365			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	3.50E-04	71.35
Repeatability	6.10E-05	12.45
Reproducibility	2.89E-04	58.90
Operator	1.36E-04	27.69
Operator*Part	1.53E-04	31.21
Part-To-Part	1.40E-04	28.65
Total Variation	4.90E-04	100.00

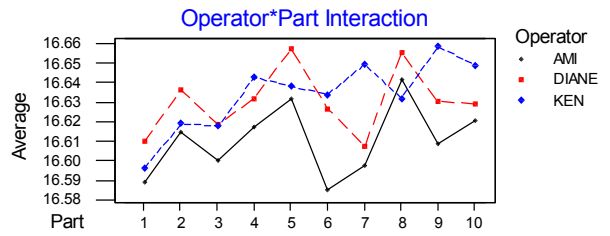
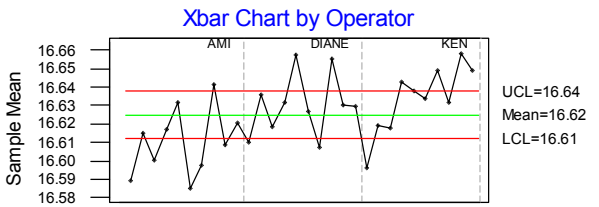
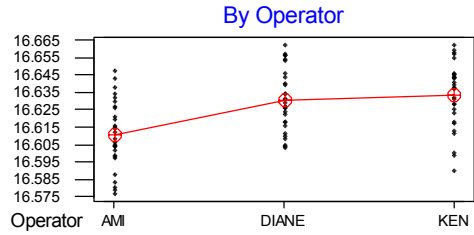
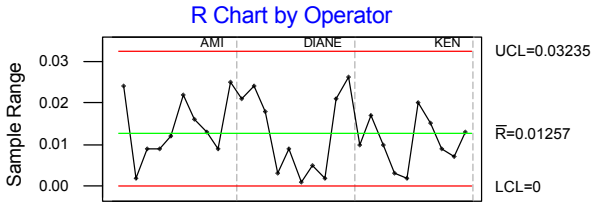
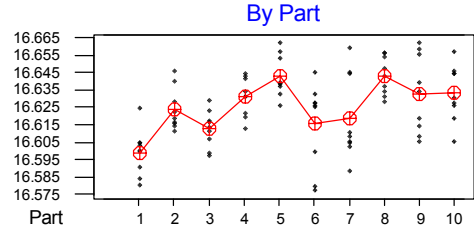
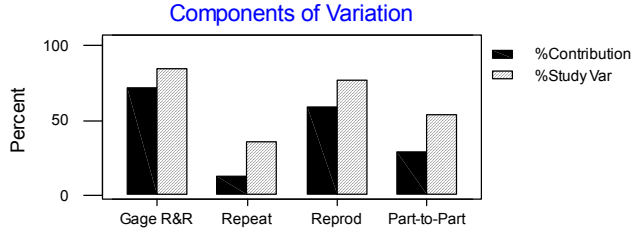
Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	1.87E-02	0.096281	84.47
Repeatability	7.81E-03	0.040219	35.28
Reproducibility	1.70E-02	0.087478	76.75
Operator	1.16E-02	0.059977	52.62
Operator*Part	1.24E-02	0.063680	55.87
Part-To-Part	1.18E-02	0.061013	53.53
Total Variation	2.21E-02	0.113985	100.00

Number of Distinct Categories = 1

Gage R&R for 16.66

CMMS16.66

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:



Gage R&R Study - ANOVA Method

Gage R&R for 22.68

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0370648	0.0041183	5.3623	0.00123
Operator	2	0.0110834	0.0055417	7.2157	0.00500
Operator*Part	18	0.0138242	0.0007680	11.5606	0.00000
Repeatability	60	0.0039860	0.0000664		
Total	89	0.0659584			

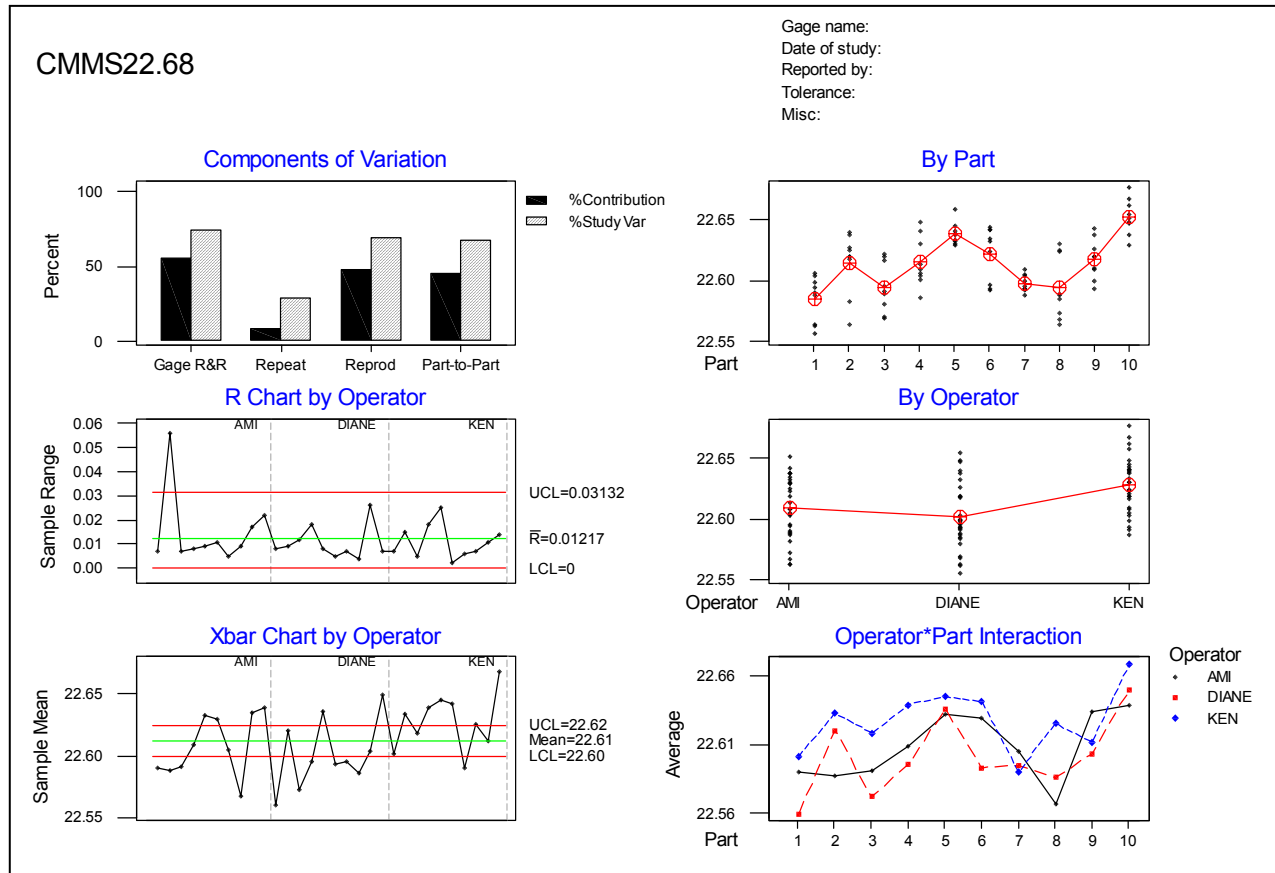
Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	4.59E-04	55.24
Repeatability	6.64E-05	7.99
Reproducibility	3.93E-04	47.25
Operator	1.59E-04	19.13
Operator*Part	2.34E-04	28.12
Part-To-Part	3.72E-04	44.76
Total Variation	8.32E-04	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	2.14E-02	0.110385	74.32
Repeatability	8.15E-03	0.041976	28.26
Reproducibility	1.98E-02	0.102092	68.74
Operator	1.26E-02	0.064964	43.74
Operator*Part	1.53E-02	0.078756	53.03
Part-To-Part	1.93E-02	0.099364	66.90
Total Variation	2.88E-02	0.148519	100.00

Number of Distinct Categories = 1

Gage R&R for 22.68



Gage R&R Study - ANOVA Method

Gage R&R for 1.63a

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0036834	0.0004093	4.53179	0.00312
Operator	2	0.0007504	0.0003752	4.15471	0.03284
Operator*Part	18	0.0016256	0.0000903	6.01620	0.00000
Repeatability	60	0.0009007	0.0000150		
Total	89	0.0069601			

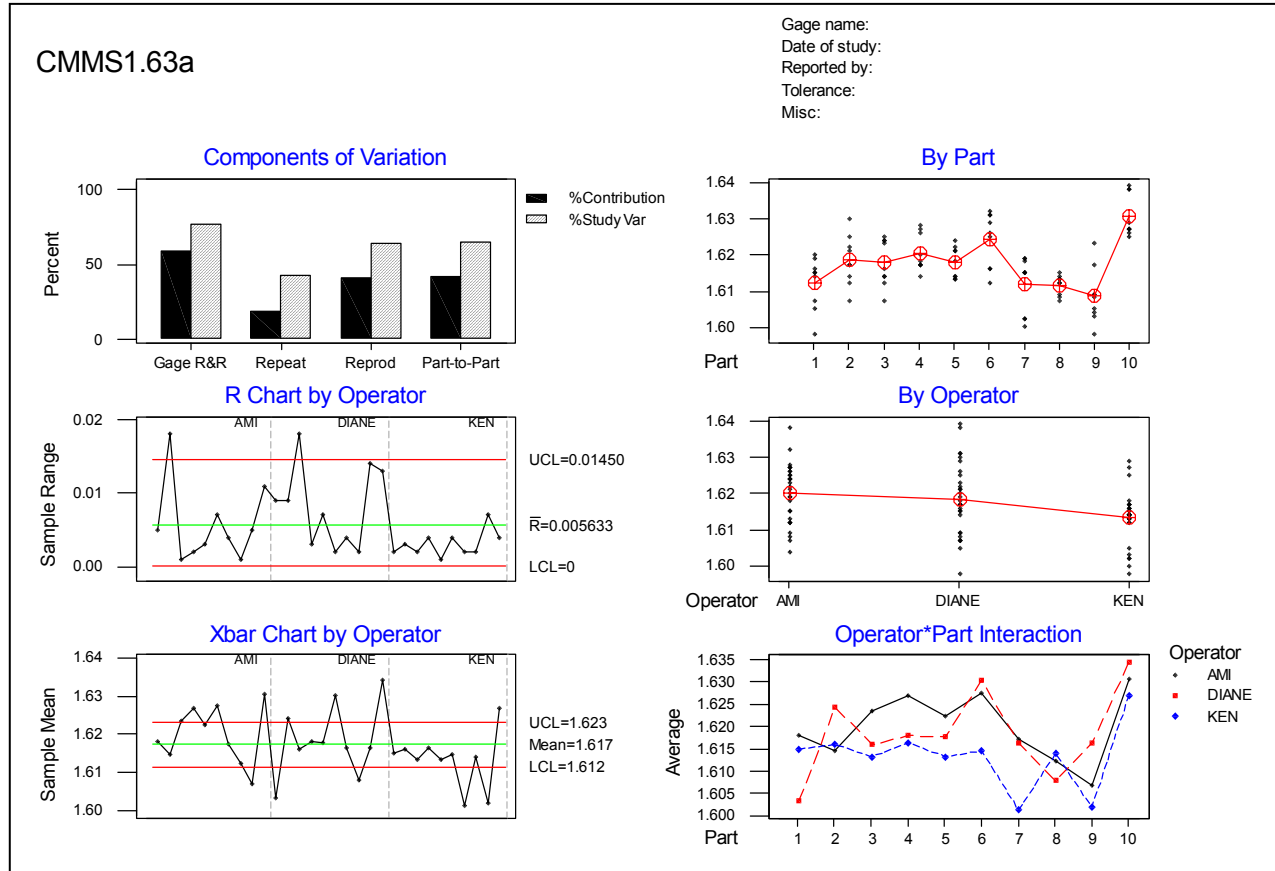
Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	4.96E-05	58.33
Repeatability	1.50E-05	17.65
Reproducibility	3.46E-05	40.68
Operator	9.50E-06	11.17
Operator*Part	2.51E-05	29.51
Part-To-Part	3.54E-05	41.67
Total Variation	8.50E-05	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	7.04E-03	3.63E-02	76.37
Repeatability	3.87E-03	2.00E-02	42.01
Reproducibility	5.88E-03	3.03E-02	63.78
Operator	3.08E-03	1.59E-02	33.42
Operator*Part	5.01E-03	2.58E-02	54.33
Part-To-Part	5.95E-03	3.07E-02	64.55
Total Variation	9.22E-03	4.75E-02	100.00

Number of Distinct Categories = 1

Gage R&R for 1.63a



Gage R&R Study - ANOVA Method

Gage R&R for 25.44

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.11229	0.012476	1.7508	0.14906
Operator	2	0.84533	0.422665	59.3137	0.00000
Operator*Part	18	0.12827	0.007126	0.9748	0.49920
Repeatability	60	0.43861	0.007310		
Total	89	1.52449			

Two-Way ANOVA Table Without Interaction

Source	DF	SS	MS	F	P
Part	9	0.11229	0.012476	1.7167	0.09916
Operator	2	0.84533	0.422665	58.1567	0.00000
Repeatability	78	0.56688	0.007268		
Total	89	1.52449			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.021114	97.33
Repeatability	0.007268	33.50
Reproducibility	0.013847	63.83
Operator	0.013847	63.83
Part-To-Part	0.000579	2.67
Total Variation	0.021693	100.00

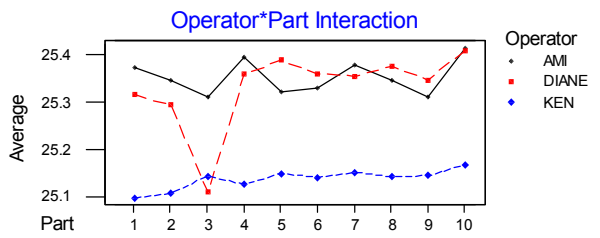
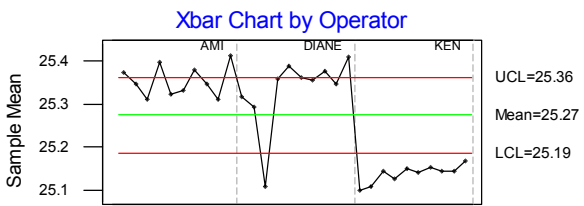
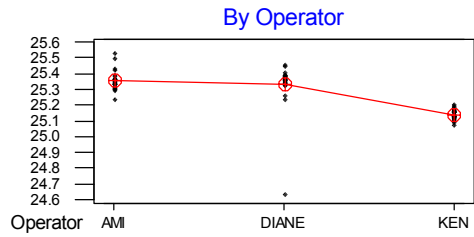
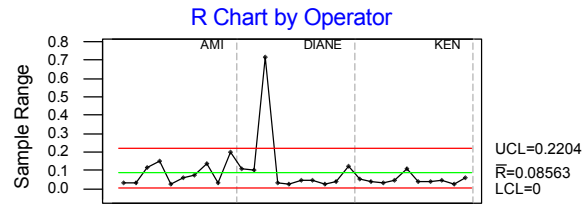
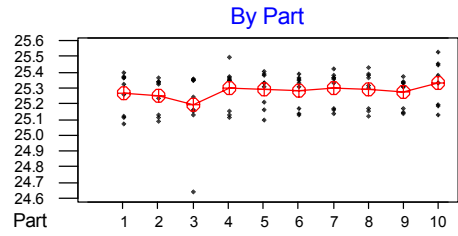
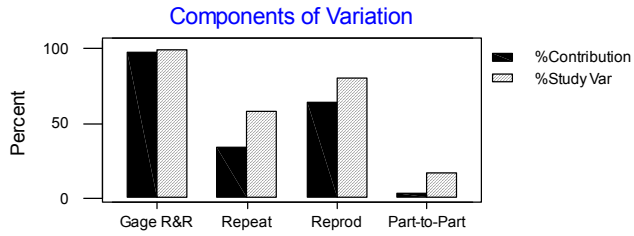
Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	0.145307	0.748333	98.66
Repeatability	0.085251	0.439041	57.88
Reproducibility	0.117671	0.606008	79.89
Operator	0.117671	0.606008	79.89
Part-To-Part	0.024056	0.123891	16.33
Total Variation	0.147285	0.758520	100.00

Number of Distinct Categories = 0

Gage R&R for 25.44

CMMS25.44

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:



Gage R&R Study - ANOVA Method

Gage R&R for 1.00

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0413668	0.0045963	36.7411	0.00000
Operator	2	0.0033669	0.0016834	13.4567	0.00027
Operator*Part	18	0.0022518	0.0001251	2.4767	0.00455
Repeatability	60	0.0030307	0.0000505		
Total	89	0.0500161			

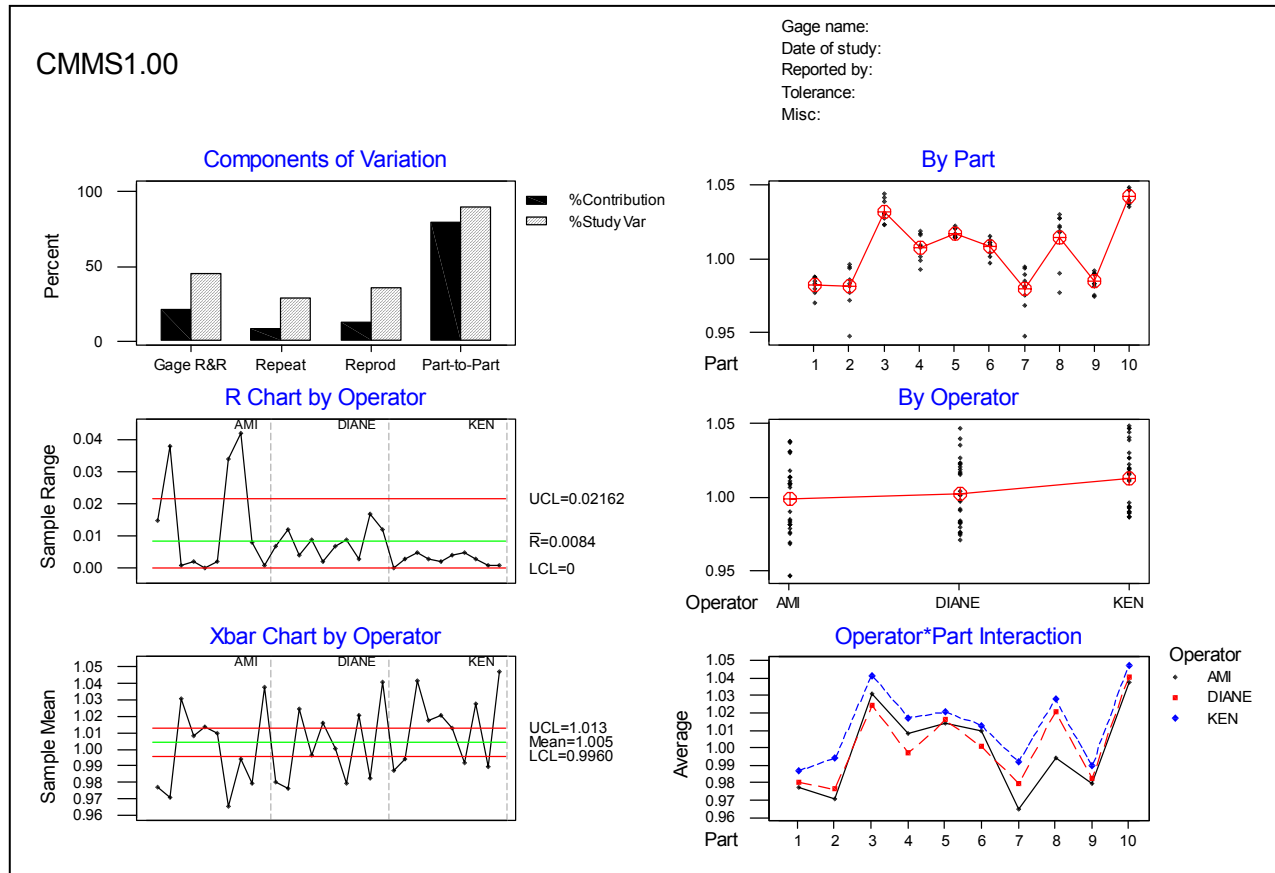
Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	1.27E-04	20.40
Repeatability	5.05E-05	8.09
Reproducibility	7.68E-05	12.31
Operator	5.19E-05	8.32
Operator*Part	2.49E-05	3.98
Part-To-Part	4.97E-04	79.60
Total Variation	6.24E-04	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	1.13E-02	0.058110	45.17
Repeatability	7.11E-03	0.036602	28.45
Reproducibility	8.76E-03	0.045135	35.08
Operator	7.21E-03	0.037117	28.85
Operator*Part	4.99E-03	0.025679	19.96
Part-To-Part	2.23E-02	0.114789	89.22
Total Variation	2.50E-02	0.128659	100.00

Number of Distinct Categories = 3

Gage R&R for 1.00



Gage R&R Study - ANOVA Method

Gage R&R for 38.03

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0066830	0.0007426	17.9495	0.00000
Operator	2	0.0007194	0.0003597	8.6944	0.00228
Operator*Part	18	0.0007446	0.0000414	1.0302	0.44177
Repeatability	60	0.0024093	0.0000402		
Total	89	0.0105563			

Two-Way ANOVA Table Without Interaction

Source	DF	SS	MS	F	P
Part	9	0.0066830	0.0007426	18.3639	0.00000
Operator	2	0.0007194	0.0003597	8.8951	0.00033
Repeatability	78	0.0031540	0.0000404		
Total	89	0.0105563			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	5.11E-05	39.57
Repeatability	4.04E-05	31.32
Reproducibility	1.06E-05	8.24
Operator	1.06E-05	8.24
Part-To-Part	7.80E-05	60.43
Total Variation	1.29E-04	100.00

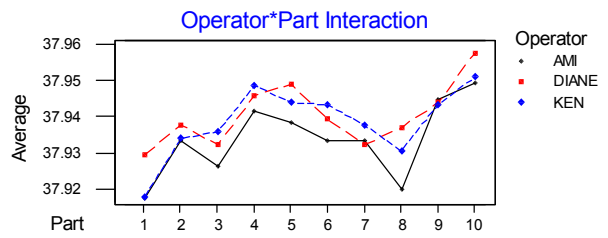
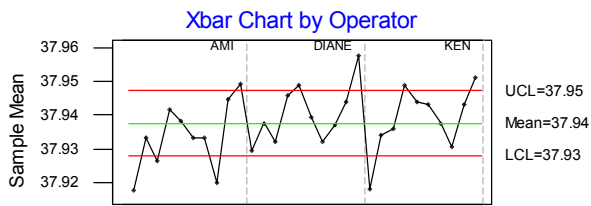
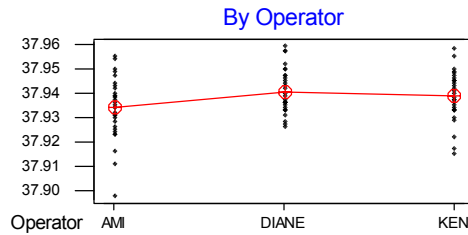
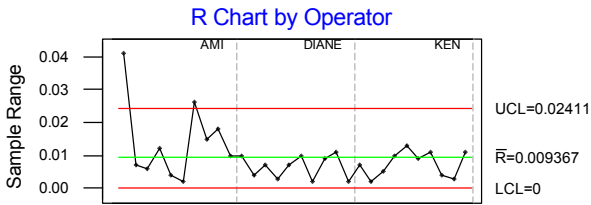
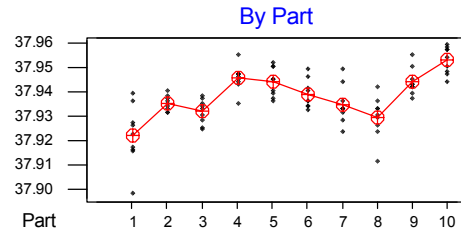
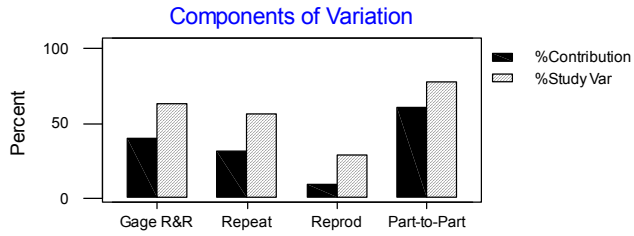
Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	7.15E-03	3.68E-02	62.90
Repeatability	6.36E-03	3.27E-02	55.97
Reproducibility	3.26E-03	1.68E-02	28.71
Operator	3.26E-03	1.68E-02	28.71
Part-To-Part	8.83E-03	4.55E-02	77.74
Total Variation	1.14E-02	5.85E-02	100.00

Number of Distinct Categories = 2

Gage R&R for 38.03

CMMS38.03

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:



Gage R&R Study - ANOVA Method

Gage R&R for 40.34

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0199172	0.0022130	316.648	0.00000
Operator	2	0.0004269	0.0002134	30.539	0.00000
Operator*Part	18	0.0001258	0.0000070	1.176	0.30950
Repeatability	60	0.0003567	0.0000059		
Total	89	0.0208265			

Two-Way ANOVA Table Without Interaction

Source	DF	SS	MS	F	P
Part	9	0.0199172	0.0022130	357.777	0.00000
Operator	2	0.0004269	0.0002134	34.506	0.00000
Repeatability	78	0.0004825	0.0000062		
Total	89	0.0208265			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	1.31E-05	5.07
Repeatability	6.19E-06	2.39
Reproducibility	6.91E-06	2.67
Operator	6.91E-06	2.67
Part-To-Part	2.45E-04	94.93
Total Variation	2.58E-04	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	3.62E-03	1.86E-02	22.51
Repeatability	2.49E-03	1.28E-02	15.47
Reproducibility	2.63E-03	1.35E-02	16.35
Operator	2.63E-03	1.35E-02	16.35
Part-To-Part	1.57E-02	8.06E-02	97.43
Total Variation	1.61E-02	8.28E-02	100.00

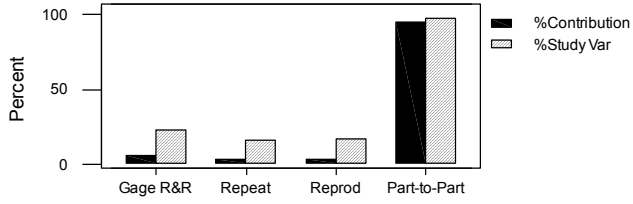
Number of Distinct Categories = 6

Gage R&R for 40.34

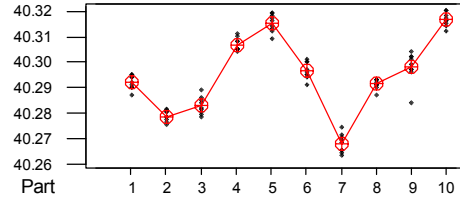
CMMS40.34

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:

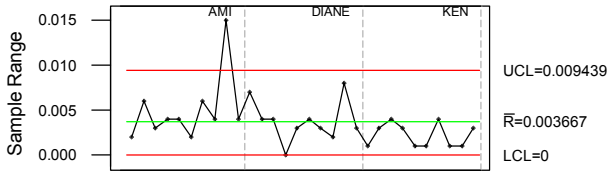
Components of Variation



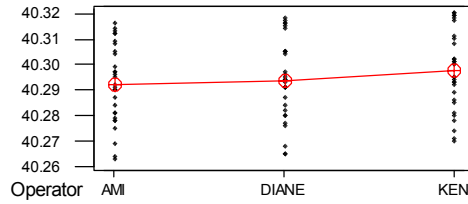
By Part



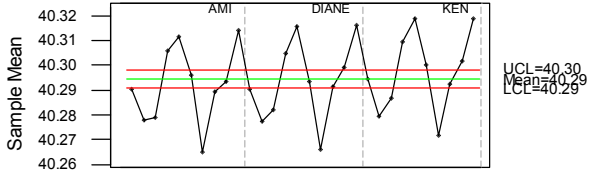
R Chart by Operator



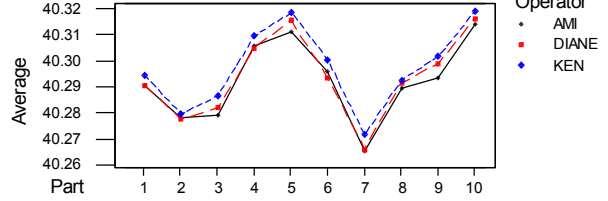
By Operator



Xbar Chart by Operator



Operator*Part Interaction



Gage R&R Study - ANOVA Method

Gage R&R for 1.63b

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.049742	0.0055269	3.3441	0.01403
Operator	2	0.067277	0.0336386	20.3531	0.00002
Operator*Part	18	0.029750	0.0016528	6.1563	0.00000
Repeatability	60	0.016108	0.0002685		
Total	89	0.162877			

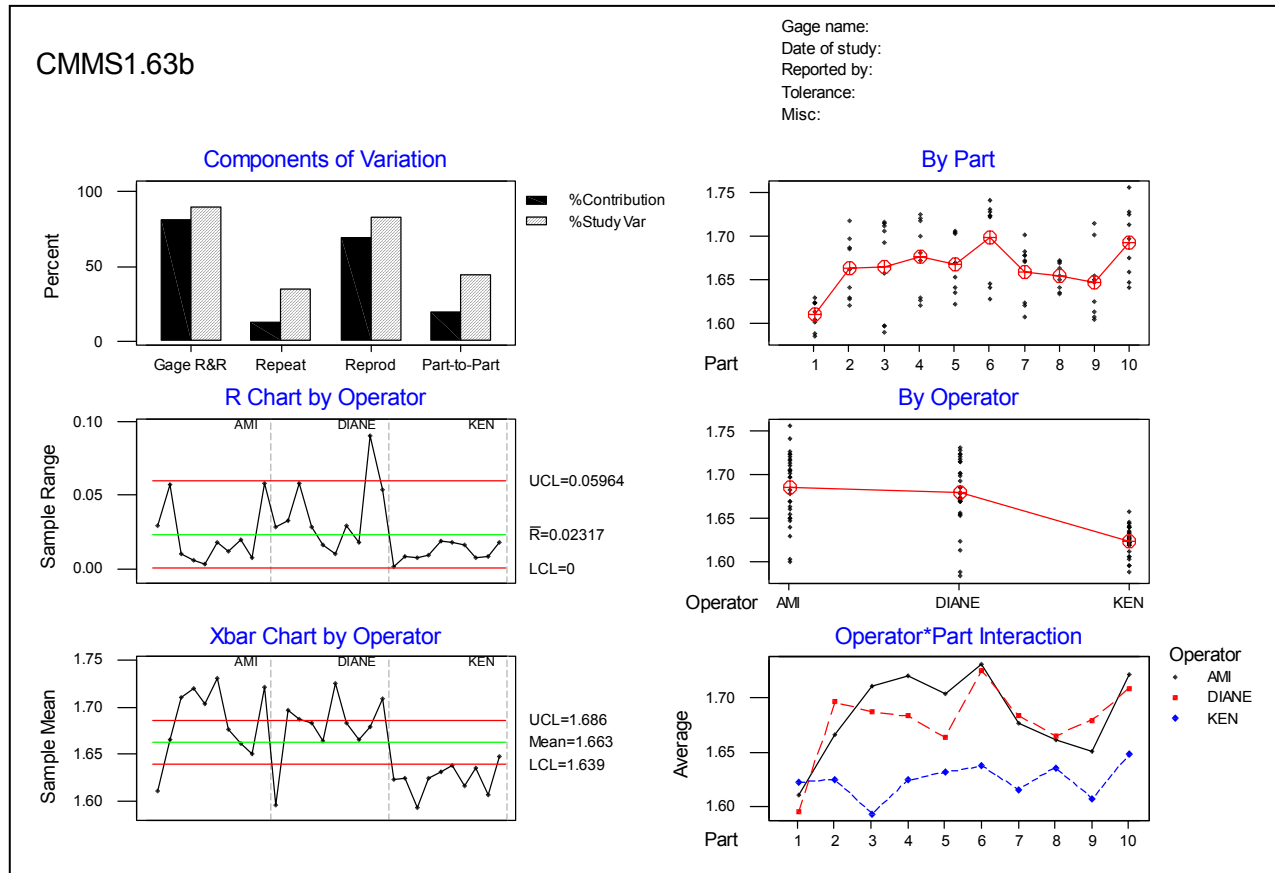
Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	1.80E-03	80.67
Repeatability	2.68E-04	12.06
Reproducibility	1.53E-03	68.61
Operator	1.07E-03	47.89
Operator*Part	4.61E-04	20.72
Part-To-Part	4.30E-04	19.33
Total Variation	2.23E-03	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	4.24E-02	0.218258	89.81
Repeatability	1.64E-02	0.084383	34.72
Reproducibility	3.91E-02	0.201287	82.83
Operator	3.27E-02	0.168161	69.20
Operator*Part	2.15E-02	0.110627	45.52
Part-To-Part	2.07E-02	0.106850	43.97
Total Variation	4.72E-02	0.243010	100.00

Number of Distinct Categories = 1

Gage R&R for 1.63b



Gage R&R Study - ANOVA Method

Gage R&R for 2.91

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0810063	0.0090007	76.6645	0.00000
Operator	2	0.0031901	0.0015950	13.5859	0.00025
Operator*Part	18	0.0021133	0.0001174	1.8775	0.03593
Repeatability	60	0.0037520	0.0000625		
Total	89	0.0900616			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	1.30E-04	11.64
Repeatability	6.25E-05	5.60
Reproducibility	6.75E-05	6.05
Operator	4.93E-05	4.41
Operator*Part	1.83E-05	1.64
Part-To-Part	9.87E-04	88.36
Total Variation	1.12E-03	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	1.14E-02	0.058737	34.12
Repeatability	7.91E-03	0.040725	23.66
Reproducibility	8.22E-03	0.042325	24.59
Operator	7.02E-03	0.036143	21.00
Operator*Part	4.28E-03	0.022025	12.80
Part-To-Part	3.14E-02	0.161798	94.00
Total Variation	3.34E-02	0.172129	100.00

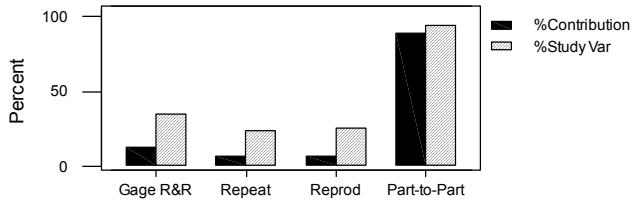
Number of Distinct Categories = 4

Gage R&R for 2.91

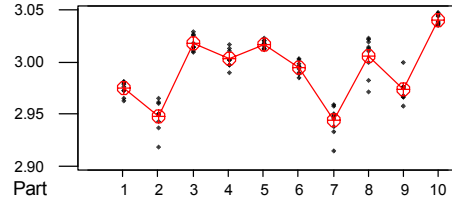
CMMS2.91

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:

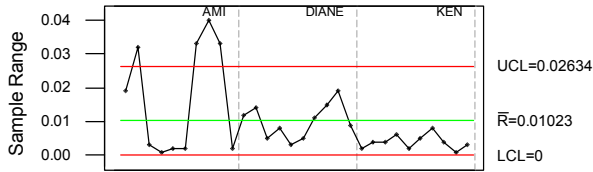
Components of Variation



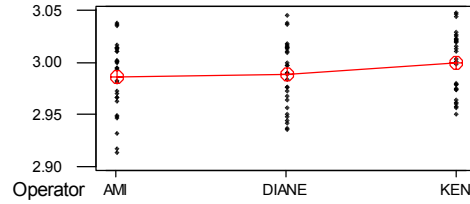
By Part



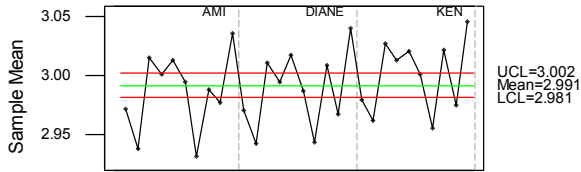
R Chart by Operator



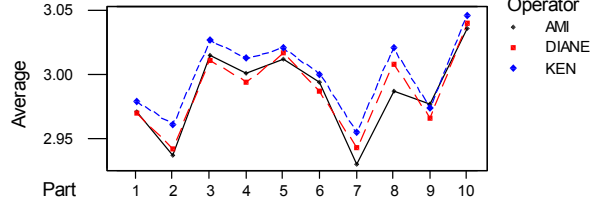
By Operator



Xbar Chart by Operator



Operator*Part Interaction



Gage R&R Study - ANOVA Method

Gage R&R for 40.1

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.099556	0.0110617	3.65714	0.00924
Operator	2	0.050000	0.0250000	8.26531	0.00284
Operator*Part	18	0.054444	0.0030247	1.81481	0.04431
Repeatability	60	0.100000	0.0016667		
Total	89	0.304000			

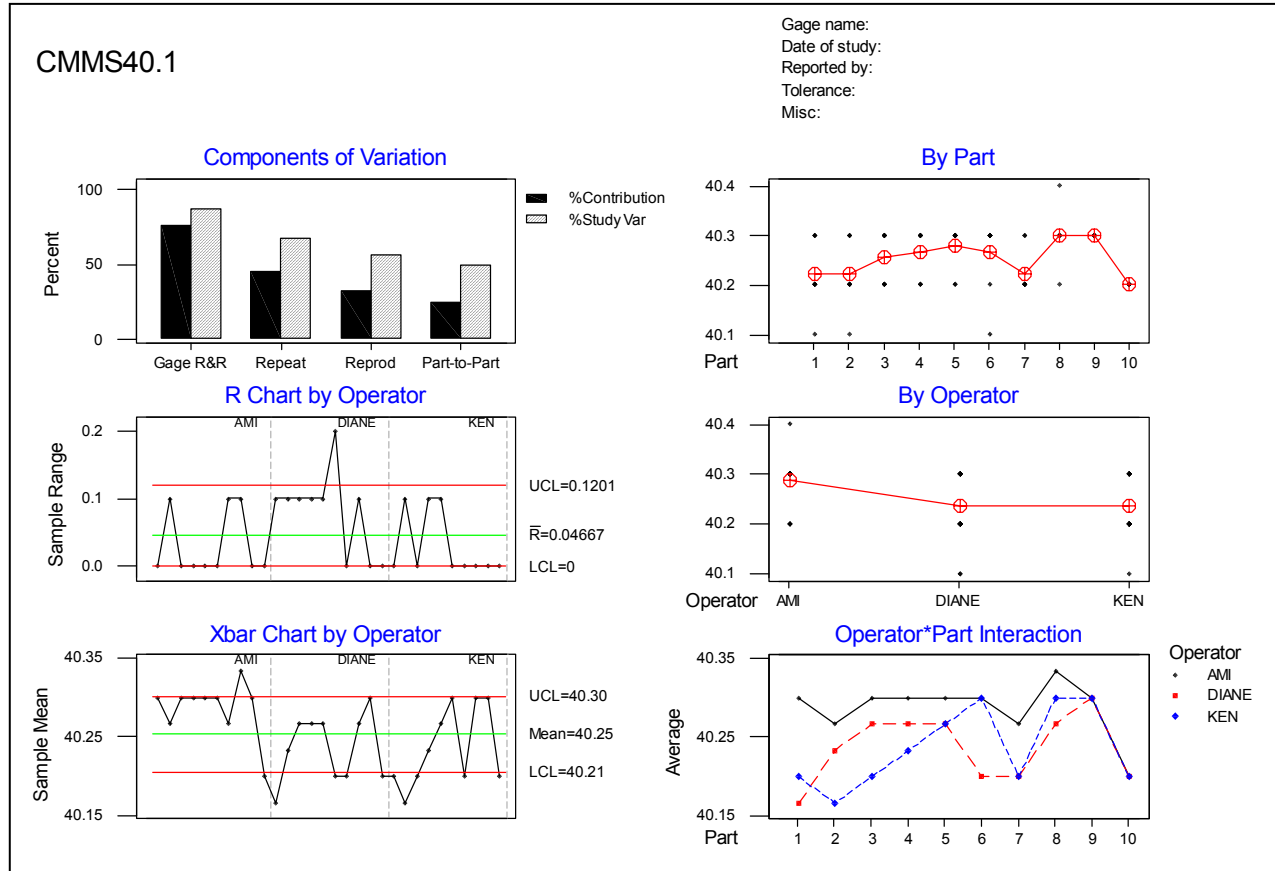
Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	2.85E-03	76.15
Repeatability	1.67E-03	44.51
Reproducibility	1.19E-03	31.65
Operator	7.33E-04	19.56
Operator*Part	4.53E-04	12.09
Part-To-Part	8.93E-04	23.85
Total Variation	3.74E-03	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	5.34E-02	0.275024	87.27
Repeatability	4.08E-02	0.210248	66.71
Reproducibility	3.44E-02	0.177297	56.26
Operator	2.71E-02	0.139384	44.23
Operator*Part	2.13E-02	0.109572	34.77
Part-To-Part	2.99E-02	0.153898	48.83
Total Variation	6.12E-02	0.315155	100.00

Number of Distinct Categories = 1

Gage R&R for 40.1



Gage R&R Study - ANOVA Method

Gage R&R for 145

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.115667	0.0128519	1.81675	0.13432
Operator	2	0.072667	0.0363333	5.13613	0.01719
Operator*Part	18	0.127333	0.0070741	0.89671	0.58448
Repeatability	60	0.473333	0.0078889		
Total	89	0.789000			

Two-Way ANOVA Table Without Interaction

Source	DF	SS	MS	F	P
Part	9	0.115667	0.0128519	1.66889	0.11084
Operator	2	0.072667	0.0363333	4.71809	0.01163
Repeatability	78	0.600667	0.0077009		
Total	89	0.789000			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	8.66E-03	93.80
Repeatability	7.70E-03	83.45
Reproducibility	9.54E-04	10.34
Operator	9.54E-04	10.34
Part-To-Part	5.72E-04	6.20
Total Variation	9.23E-03	100.00

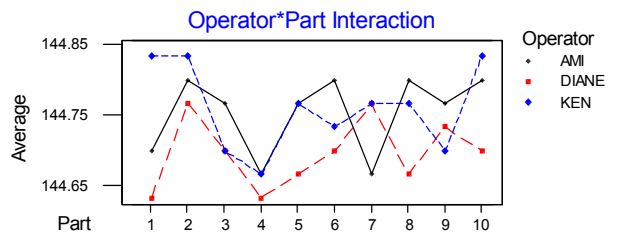
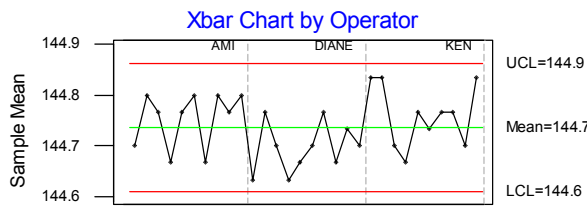
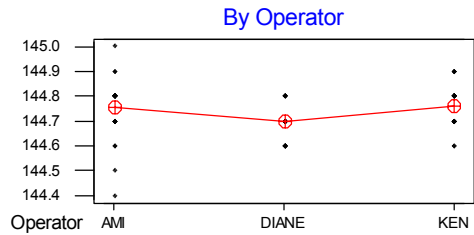
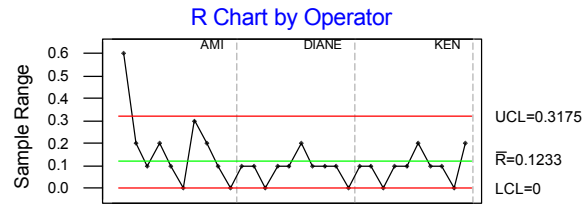
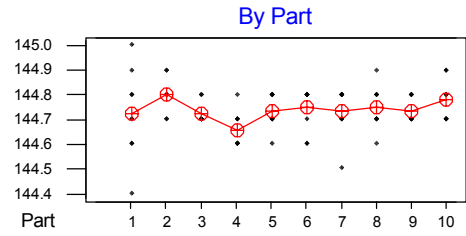
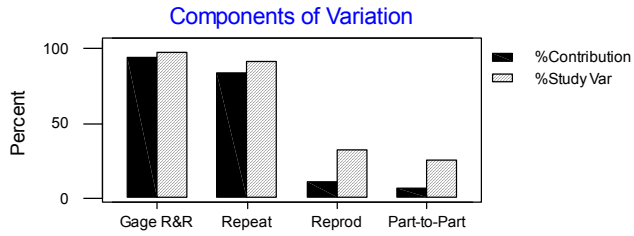
Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	9.30E-02	0.479124	96.85
Repeatability	8.78E-02	0.451936	91.35
Reproducibility	3.09E-02	0.159102	32.16
Operator	3.09E-02	0.159102	32.16
Part-To-Part	2.39E-02	0.123206	24.90
Total Variation	9.61E-02	0.494711	100.00

Number of Distinct Categories = 0

Gage R&R for 145

CMMS145

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:



Gage R&R Study - ANOVA Method

Gage R&R for 13.78

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0109064	0.0012118	6.4905	0.00039
Operator	2	0.0045648	0.0022824	12.2245	0.00044
Operator*Part	18	0.0033607	0.0001867	2.1911	0.01229
Repeatability	60	0.0051127	0.0000852		
Total	89	0.0239446			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	1.89E-04	62.38
Repeatability	8.52E-05	28.14
Reproducibility	1.04E-04	34.24
Operator	6.99E-05	23.07
Operator*Part	3.38E-05	11.17
Part-To-Part	1.14E-04	37.62
Total Variation	3.03E-04	100.00

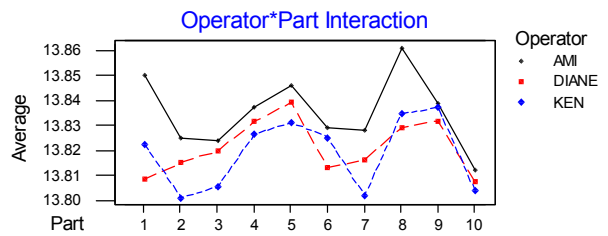
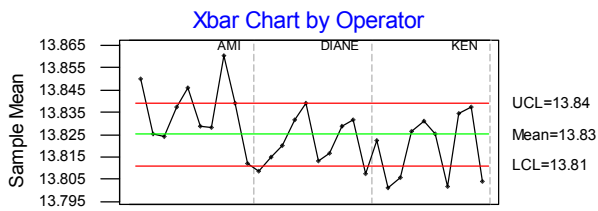
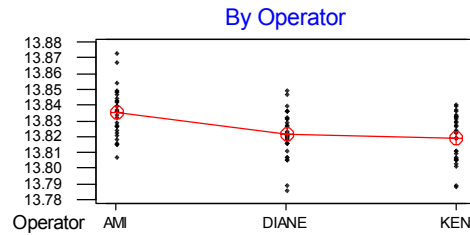
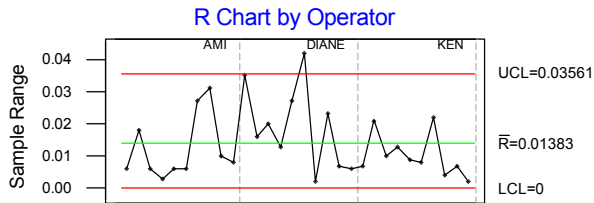
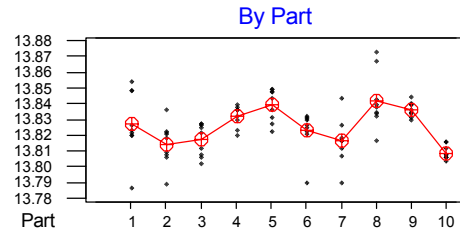
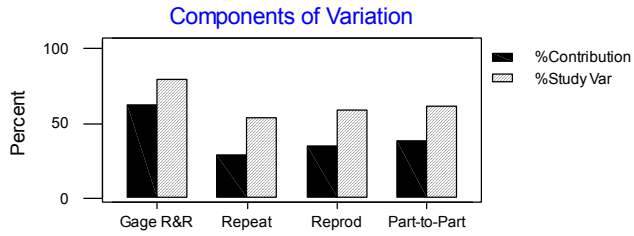
Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	1.37E-02	7.08E-02	78.98
Repeatability	9.23E-03	4.75E-02	53.05
Reproducibility	1.02E-02	5.24E-02	58.52
Operator	8.36E-03	4.30E-02	48.03
Operator*Part	5.82E-03	3.00E-02	33.43
Part-To-Part	1.07E-02	5.50E-02	61.33
Total Variation	1.74E-02	8.96E-02	100.00

Number of Distinct Categories = 1

Gage R&R for 13.78

CMMS13.78

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:



APPENDIX (c)

Data results for FARO arm (Round)

Gage R&R Study - ANOVA Method

Gage R&R for 4.94

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0019058	0.0002118	12.9479	0.00000
Operator	2	0.0000494	0.0000247	1.5103	0.24754
Operator*Part	18	0.0002944	0.0000164	3.0348	0.00065
Repeatability	60	0.0003233	0.0000054		
Total	89	0.0025729			

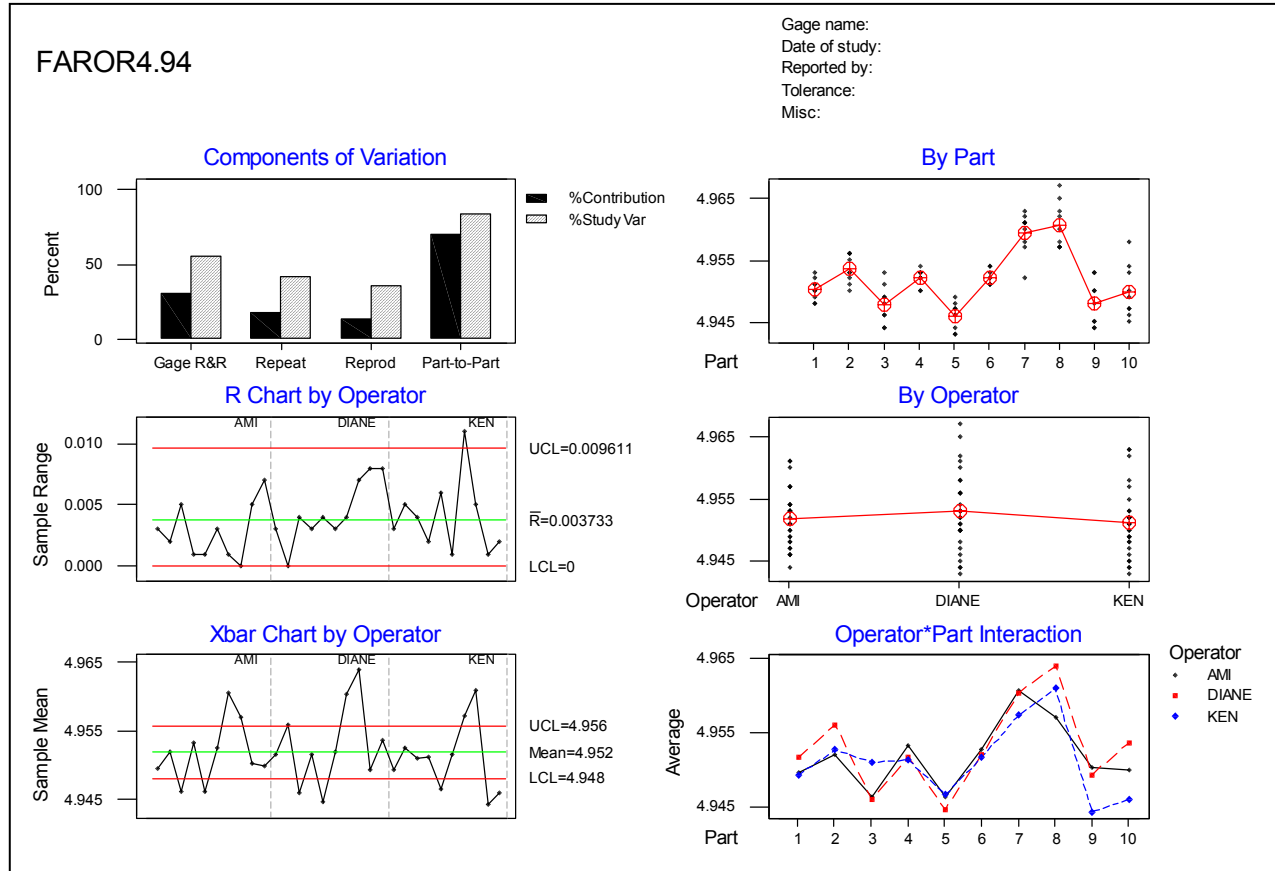
Gage R&R

Source	VarComp	%Contribution (of VarComp)	
Total Gage R&R	9.32E-06	30.04	
Repeatability	5.39E-06	17.36	
Reproducibility	3.93E-06	12.67	
Operator	2.78E-07	0.90	
Operator*Part	3.66E-06	11.78	
Part-To-Part	2.17E-05	69.96	
Total Variation	3.10E-05	100.00	

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	3.05E-03	1.57E-02	54.81
Repeatability	2.32E-03	1.20E-02	41.67
Reproducibility	1.98E-03	1.02E-02	35.60
Operator	5.27E-04	2.72E-03	9.47
Operator*Part	1.91E-03	9.85E-03	34.32
Part-To-Part	4.66E-03	2.40E-02	83.64
Total Variation	5.57E-03	2.87E-02	100.00

Number of Distinct Categories = 2

Gage R&R for 4.94



Gage R&R Study - ANOVA Method

Gage R&R for 6.63

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0130824	0.0014536	36.3232	0.00000
Operator	2	0.0006239	0.0003119	7.7950	0.00364
Operator*Part	18	0.0007203	0.0000400	2.1099	0.01627
Repeatability	60	0.0011380	0.0000190		
Total	89	0.0155646			

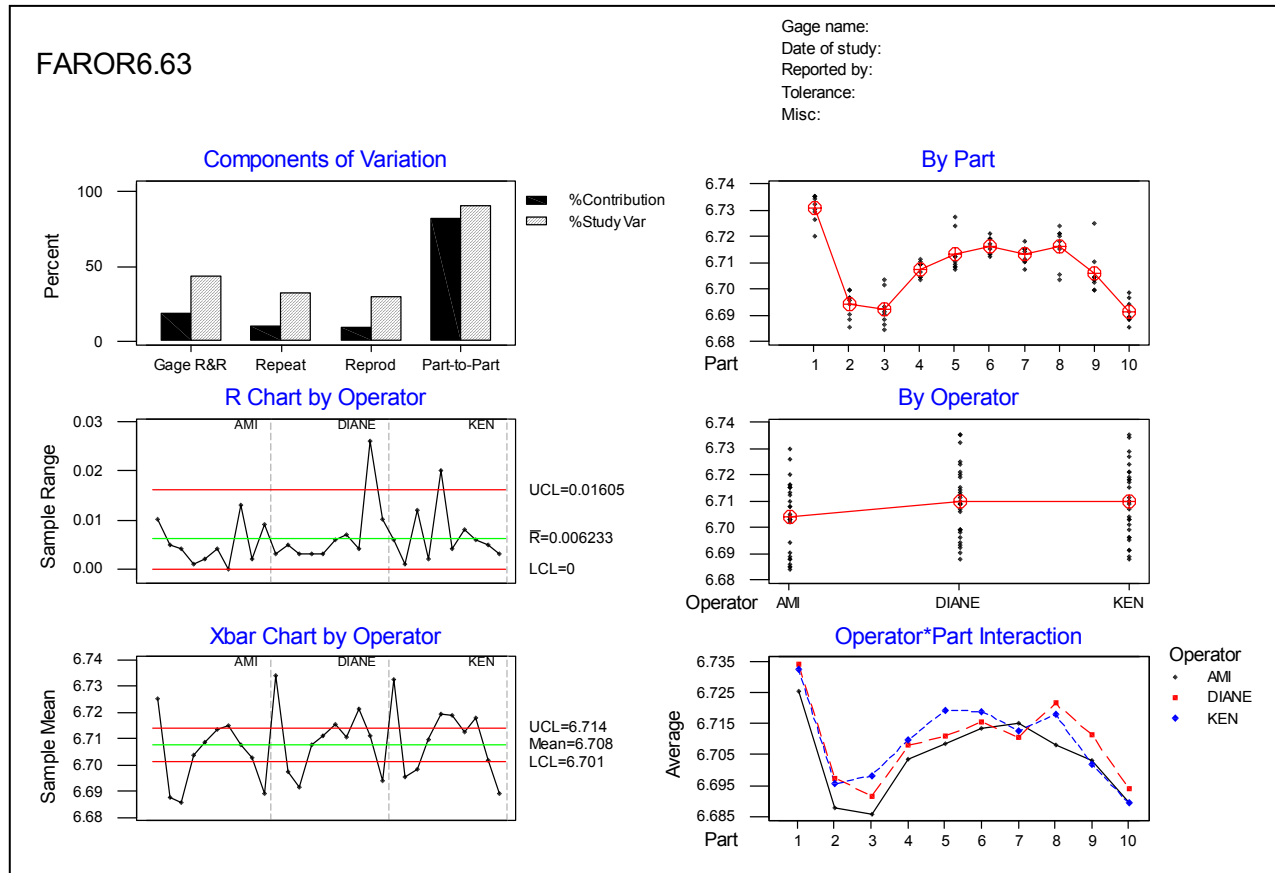
Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	3.50E-05	18.24
Repeatability	1.90E-05	9.87
Reproducibility	1.61E-05	8.37
Operator	9.06E-06	4.72
Operator*Part	7.02E-06	3.65
Part-To-Part	1.57E-04	81.76
Total Variation	1.92E-04	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	5.92E-03	3.05E-02	42.71
Repeatability	4.36E-03	2.24E-02	31.42
Reproducibility	4.01E-03	2.07E-02	28.93
Operator	3.01E-03	1.55E-02	21.72
Operator*Part	2.65E-03	1.36E-02	19.11
Part-To-Part	1.25E-02	6.45E-02	90.42
Total Variation	1.39E-02	7.14E-02	100.00

Number of Distinct Categories = 3

Gage R&R for 6.63



Gage R&R Study - ANOVA Method

Gage R&R for 29.96

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0331224	0.0036803	280.461	0.00000
Operator	2	0.0015700	0.0007850	59.823	0.00000
Operator*Part	18	0.0002362	0.0000131	1.198	0.29209
Repeatability	60	0.0006573	0.0000110		
Total	89	0.0355860			

Two-Way ANOVA Table Without Interaction

Source	DF	SS	MS	F	P
Part	9	0.0331224	0.0036803	321.265	0.00000
Operator	2	0.0015700	0.0007850	68.527	0.00000
Repeatability	78	0.0008935	0.0000115		
Total	89	0.0355860			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	3.72E-05	8.37
Repeatability	1.15E-05	2.57
Reproducibility	2.58E-05	5.80
Operator	2.58E-05	5.80
Part-To-Part	4.08E-04	91.63
Total Variation	4.45E-04	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	6.10E-03	0.031428	28.93
Repeatability	3.38E-03	0.017431	16.05
Reproducibility	5.08E-03	0.026151	24.07
Operator	5.08E-03	0.026151	24.07
Part-To-Part	2.02E-02	0.103980	95.72
Total Variation	2.11E-02	0.108626	100.00

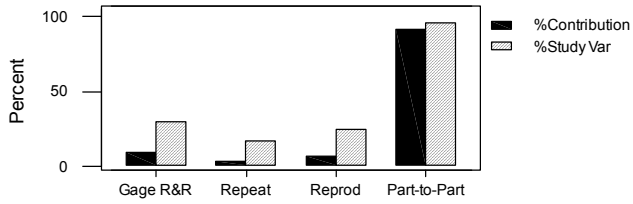
Number of Distinct Categories = 5

Gage R&R for 29.96

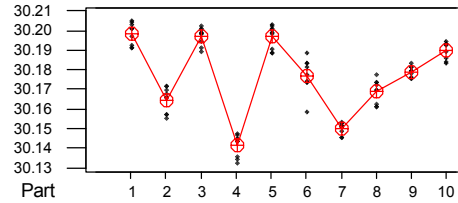
FAROR29.96

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:

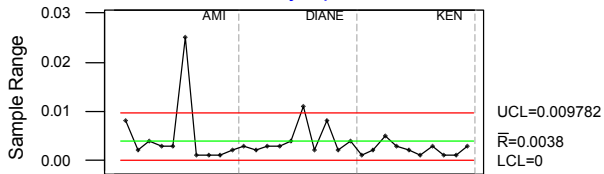
Components of Variation



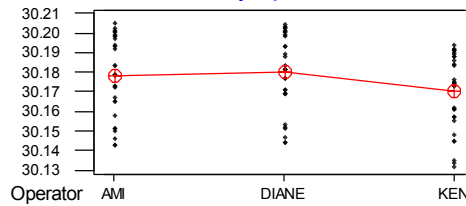
By Part



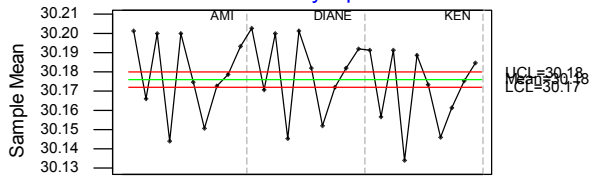
R Chart by Operator



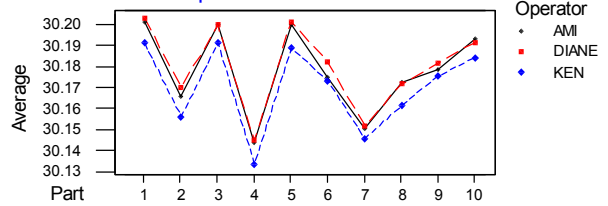
By Operator



Xbar Chart by Operator



Operator*Part Interaction



Gage R&R Study - ANOVA Method

Gage R&R for 3.82

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	1417672	157519	0.99999	0.47416
Operator	2	315013	157507	0.99991	0.38745
Operator*Part	18	2835383	157521	1.00000	0.47269
Repeatability	60	9451312	157522		
Total	89	14019381			

Two-Way ANOVA Table Without Interaction

Source	DF	SS	MS	F	P
Part	9	1417672	157519	0.999983	0.44732
Operator	2	315013	157507	0.999904	0.37258
Repeatability	78	12286695	157522		
Total	89	14019381			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	157522	100.00
Repeatability	157522	100.00
Reproducibility	0	0.00
Operator	0	0.00
Part-To-Part	0	0.00
Total Variation	157522	100.00

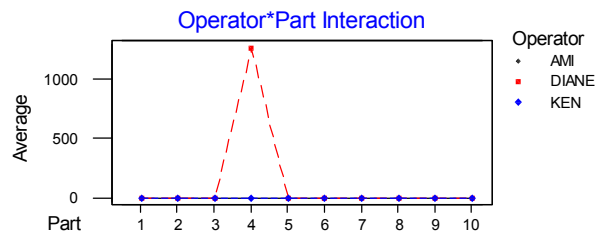
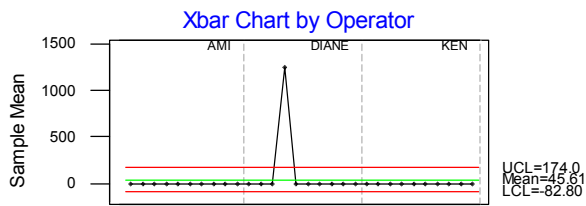
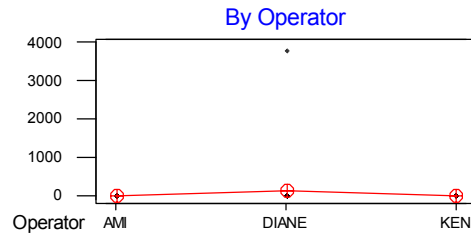
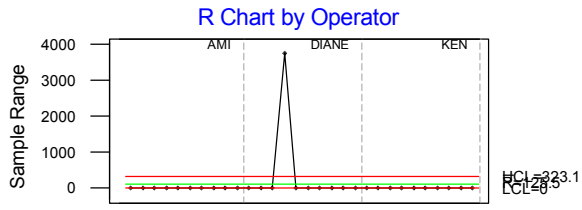
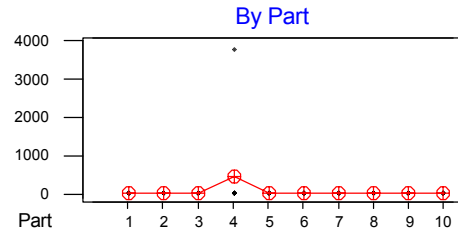
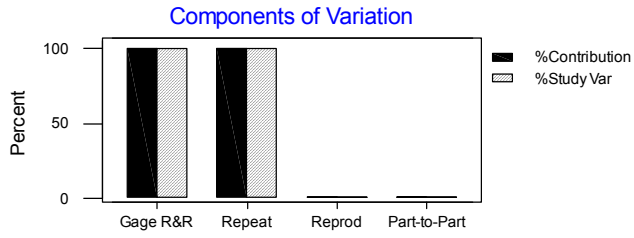
Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	396.890	2043.98	100.00
Repeatability	396.890	2043.98	100.00
Reproducibility	0.000	0.00	0.00
Operator	0.000	0.00	0.00
Part-To-Part	0.000	0.00	0.00
Total Variation	396.890	2043.98	100.00

Number of Distinct Categories = 0

Gage R&R for 3.82

FAROR3.82

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:



Gage R&R Study - ANOVA Method

Gage R&R for 14.98

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0053665	0.0005963	14.3122	0.00000
Operator	2	0.0009134	0.0004567	10.9624	0.00077
Operator*Part	18	0.0007499	0.0000417	1.6598	0.07371
Repeatability	60	0.0015060	0.0000251		
Total	89	0.0085358			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	4.45E-05	41.91
Repeatability	2.51E-05	23.66
Reproducibility	1.94E-05	18.25
Operator	1.38E-05	13.04
Operator*Part	5.52E-06	5.20
Part-To-Part	6.16E-05	58.09
Total Variation	1.06E-04	100.00

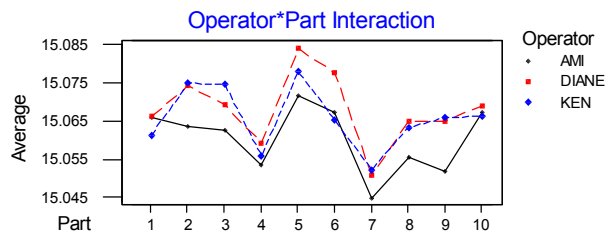
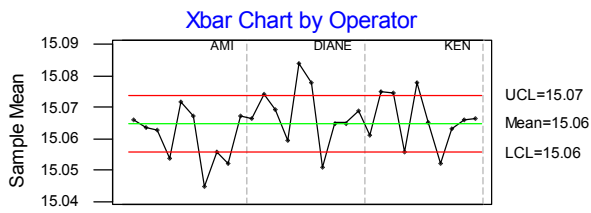
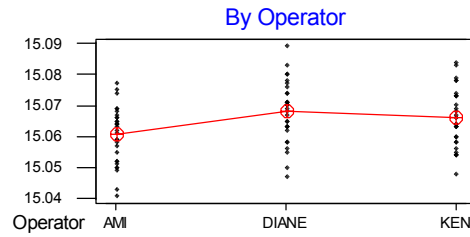
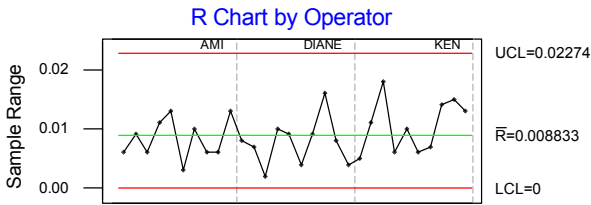
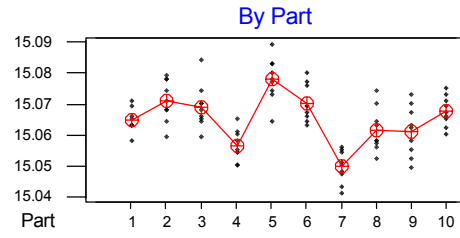
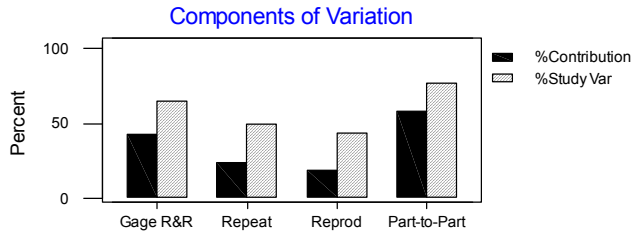
Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	6.67E-03	3.43E-02	64.74
Repeatability	5.01E-03	2.58E-02	48.64
Reproducibility	4.40E-03	2.27E-02	42.72
Operator	3.72E-03	1.92E-02	36.11
Operator*Part	2.35E-03	1.21E-02	22.81
Part-To-Part	7.85E-03	4.04E-02	76.22
Total Variation	1.03E-02	5.30E-02	100.00

Number of Distinct Categories = 2

Gage R&R for 14.98

FAROR14.98

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:



Gage R&R Study - ANOVA Method

Gage R&R for 6.38

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0062156	0.0006906	36.3059	0.00000
Operator	2	0.0022678	0.0011339	59.6098	0.00000
Operator*Part	18	0.0003424	0.0000190	0.9749	0.49904
Repeatability	60	0.0011707	0.0000195		
Total	89	0.0099965			

Two-Way ANOVA Table Without Interaction

Source	DF	SS	MS	F	P
Part	9	0.0062156	0.0006906	35.6020	0.00000
Operator	2	0.0022678	0.0011339	58.4542	0.00000
Repeatability	78	0.0015131	0.0000194		
Total	89	0.0099965			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	5.65E-05	43.12
Repeatability	1.94E-05	14.79
Reproducibility	3.72E-05	28.33
Operator	3.72E-05	28.33
Part-To-Part	7.46E-05	56.88
Total Variation	1.31E-04	100.00

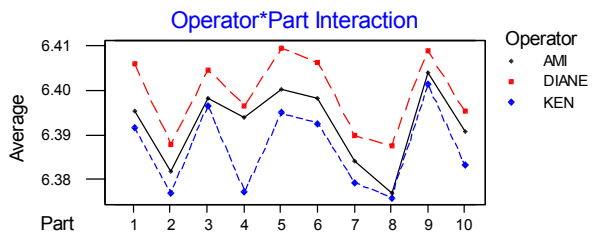
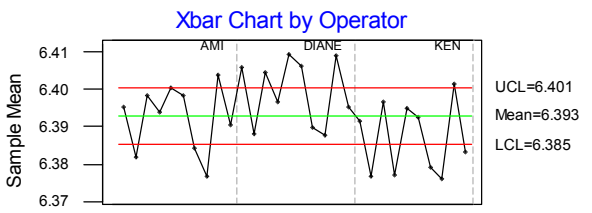
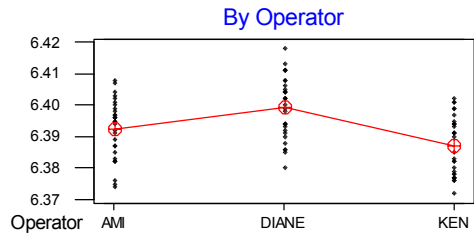
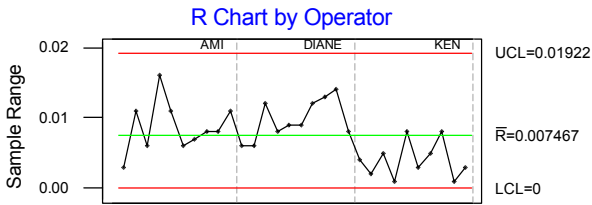
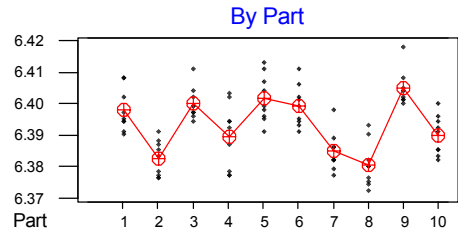
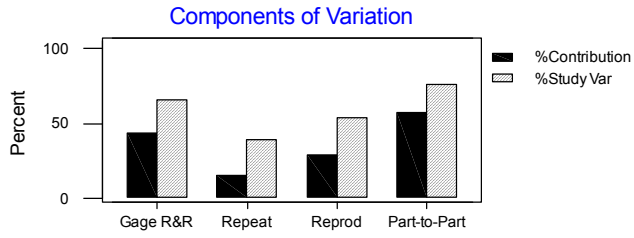
Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	7.52E-03	3.87E-02	65.67
Repeatability	4.40E-03	2.27E-02	38.46
Reproducibility	6.10E-03	3.14E-02	53.23
Operator	6.10E-03	3.14E-02	53.23
Part-To-Part	8.64E-03	4.45E-02	75.42
Total Variation	1.15E-02	5.90E-02	100.00

Number of Distinct Categories = 2

Gage R&R for 6.38

FAROR6.38

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:



Gage R&R Study - ANOVA Method

Gage R&R for 6.06

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0015059	0.0001673	8.1321	0.00009
Operator	2	0.0032299	0.0016149	78.4889	0.00000
Operator*Part	18	0.0003704	0.0000206	0.9453	0.53097
Repeatability	60	0.0013060	0.0000218		
Total	89	0.0064121			

Two-Way ANOVA Table Without Interaction

Source	DF	SS	MS	F	P
Part	9	0.0015059	0.0001673	7.7853	0.00000
Operator	2	0.0032299	0.0016149	75.1421	0.00000
Repeatability	78	0.0016764	0.0000215		
Total	89	0.0064121			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	7.46E-05	82.16
Repeatability	2.15E-05	23.67
Reproducibility	5.31E-05	58.49
Operator	5.31E-05	58.49
Part-To-Part	1.62E-05	17.84
Total Variation	9.08E-05	100.00

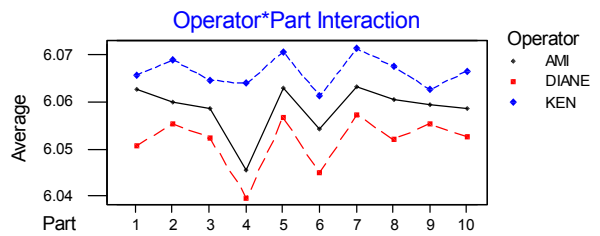
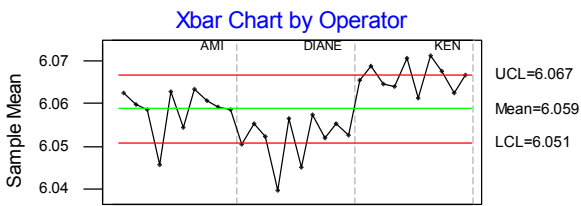
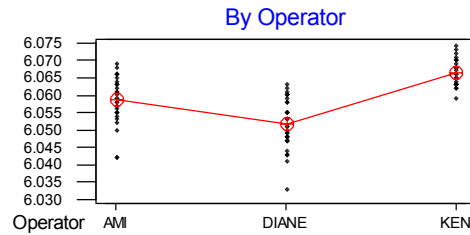
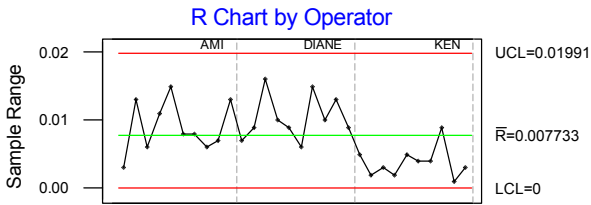
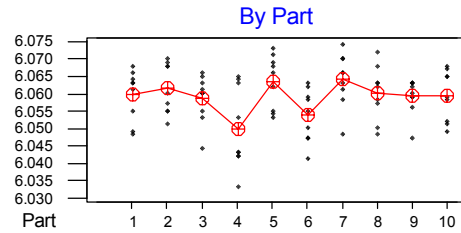
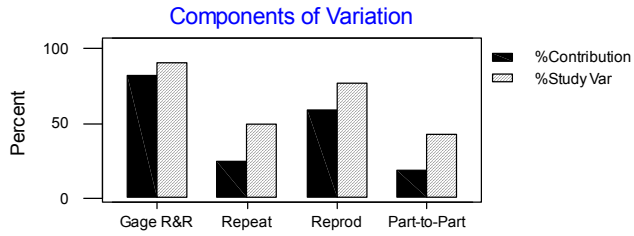
Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	8.64E-03	4.45E-02	90.64
Repeatability	4.64E-03	2.39E-02	48.65
Reproducibility	7.29E-03	3.75E-02	76.48
Operator	7.29E-03	3.75E-02	76.48
Part-To-Part	4.03E-03	2.07E-02	42.24
Total Variation	9.53E-03	4.91E-02	100.00

Number of Distinct Categories = 1

Gage R&R for 6.06

FAROR6.06

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:



APPENDIX (d)

Data Results for FARO arm (Square)

12/21/03 11:44:35 AM

Welcome to Minitab, press F1 for help.

Gage R&R Study - ANOVA Method

Gage R&R for FAROS16.66

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0087920	0.0009769	1.8548	0.12651
Operator	2	0.0307718	0.0153859	29.2125	0.00000
Operator*Part	18	0.0094804	0.0005267	4.1453	0.00002
Repeatability	60	0.0076233	0.0001271		
Total	89	0.0566676			

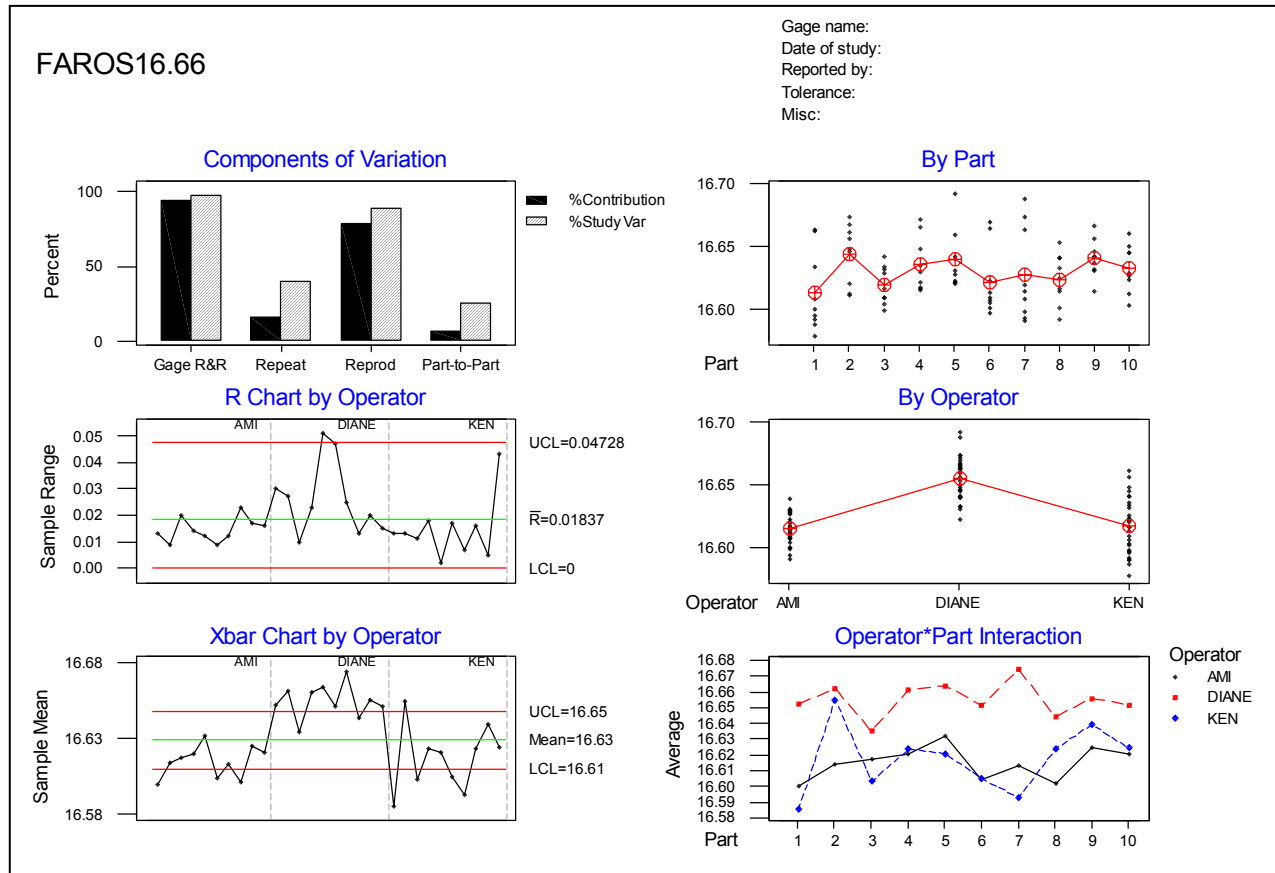
Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	7.56E-04	93.79
Repeatability	1.27E-04	15.77
Reproducibility	6.29E-04	78.02
Operator	4.95E-04	61.48
Operator*Part	1.33E-04	16.54
Part-To-Part	5.00E-05	6.21
Total Variation	8.06E-04	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	2.75E-02	0.141562	96.85
Repeatability	1.13E-02	0.058050	39.71
Reproducibility	2.51E-02	0.129112	88.33
Operator	2.23E-02	0.114616	78.41
Operator*Part	1.15E-02	0.059440	40.66
Part-To-Part	7.07E-03	0.036424	24.92
Total Variation	2.84E-02	0.146173	100.00

Number of Distinct Categories = 0

Gage R&R for FAROS16.66



Gage R&R Study - ANOVA Method

Gage R&R for FAROS22.68

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0267649	0.0029739	7.67726	0.00014
Operator	2	0.0023022	0.0011511	2.97158	0.07670
Operator*Part	18	0.0069725	0.0003874	2.76511	0.00167
Repeatability	60	0.0084053	0.0001401		
Total	89	0.0444449			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	2.48E-04	46.32
Repeatability	1.40E-04	26.17
Reproducibility	1.08E-04	20.15
Operator	2.55E-05	4.76
Operator*Part	8.24E-05	15.40
Part-To-Part	2.87E-04	53.68
Total Variation	5.35E-04	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	1.57E-02	0.081097	68.06
Repeatability	1.18E-02	0.060955	51.15
Reproducibility	1.04E-02	0.053491	44.89
Operator	5.05E-03	0.025984	21.81
Operator*Part	9.08E-03	0.046756	39.24
Part-To-Part	1.70E-02	0.087306	73.27
Total Variation	2.31E-02	0.119160	100.00

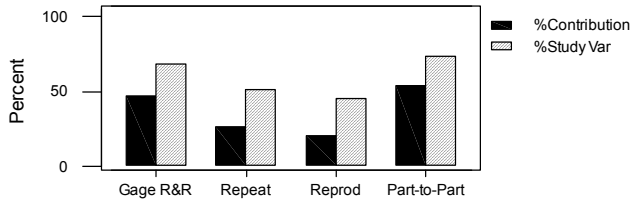
Number of Distinct Categories = 2

Gage R&R for FAROS22.68

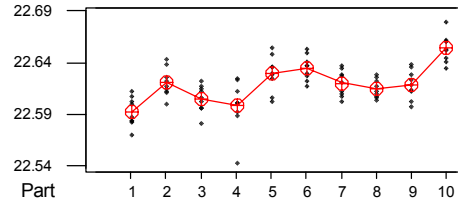
FAROS22.68

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:

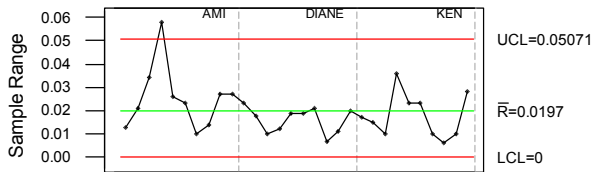
Components of Variation



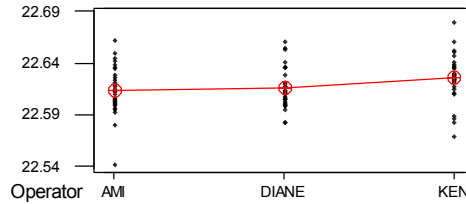
By Part



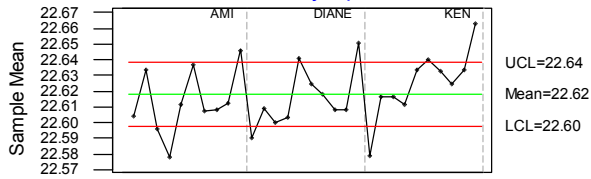
R Chart by Operator



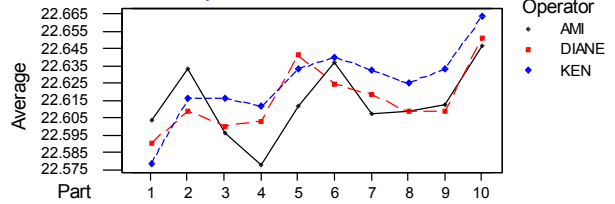
By Operator



Xbar Chart by Operator



Operator*Part Interaction



Gage R&R Study - ANOVA Method

Gage R&R for FAROS1.63a

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0057223	0.0006358	4.0026	0.00594
Operator	2	0.0033458	0.0016729	10.5313	0.00094
Operator*Part	18	0.0028593	0.0001589	7.1092	0.00000
Repeatability	60	0.0013407	0.0000223		
Total	89	0.0132681			

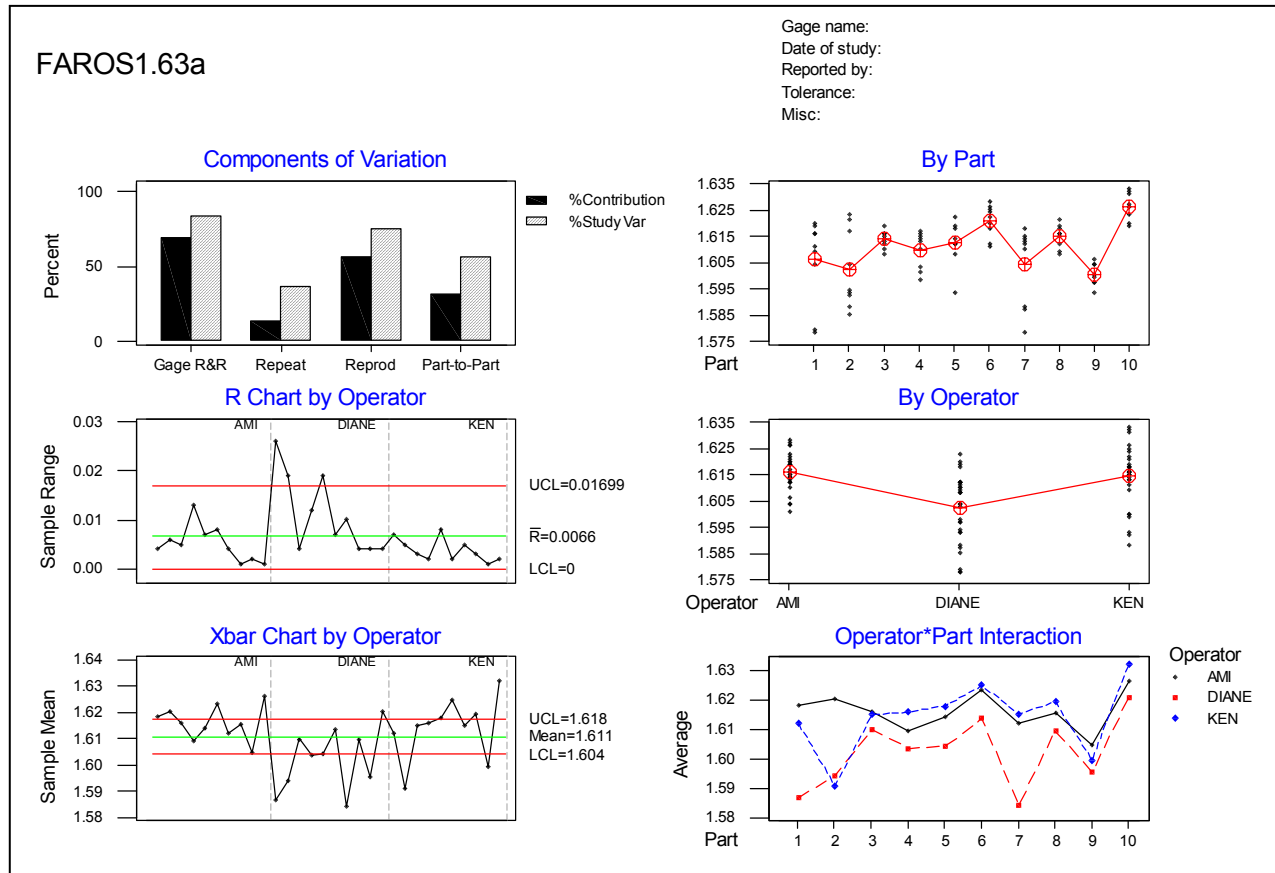
Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	1.18E-04	69.06
Repeatability	2.23E-05	13.04
Reproducibility	9.60E-05	56.02
Operator	5.05E-05	29.46
Operator*Part	4.55E-05	26.56
Part-To-Part	5.30E-05	30.94
Total Variation	1.71E-04	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	1.09E-02	5.60E-02	83.11
Repeatability	4.73E-03	2.43E-02	36.12
Reproducibility	9.80E-03	5.05E-02	74.85
Operator	7.10E-03	3.66E-02	54.28
Operator*Part	6.75E-03	3.47E-02	51.54
Part-To-Part	7.28E-03	3.75E-02	55.62
Total Variation	1.31E-02	6.74E-02	100.00

Number of Distinct Categories = 1

Gage R&R for FAROS1.63a



Gage R&R Study - ANOVA Method

Gage R&R for FAROS25.44

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.132867	0.0147630	2.2623	0.06711
Operator	2	0.156968	0.0784840	12.0272	0.00048
Operator*Part	18	0.117460	0.0065256	2.1488	0.01423
Repeatability	60	0.182209	0.0030368		
Total	89	0.589504			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	6.60E-03	87.82
Repeatability	3.04E-03	40.42
Reproducibility	3.56E-03	47.40
Operator	2.40E-03	31.92
Operator*Part	1.16E-03	15.48
Part-To-Part	9.15E-04	12.18
Total Variation	7.51E-03	100.00

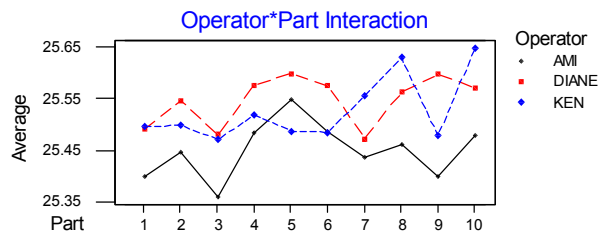
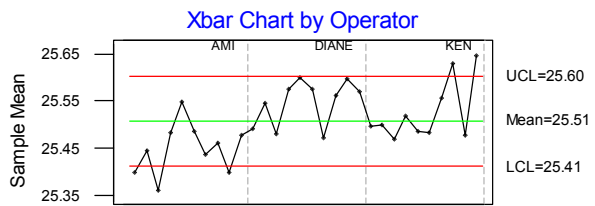
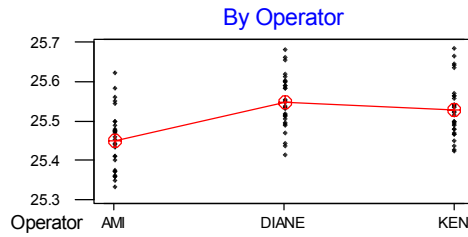
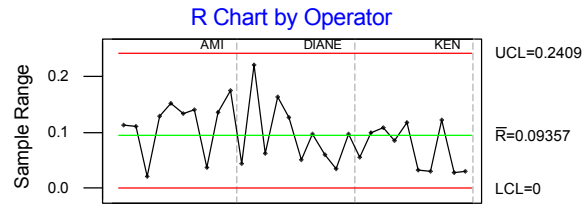
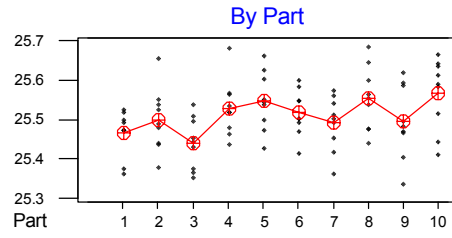
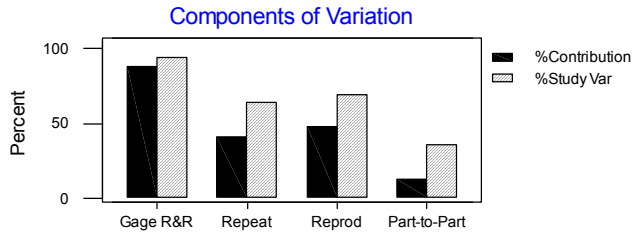
Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	8.12E-02	0.418335	93.71
Repeatability	5.51E-02	0.283802	63.57
Reproducibility	5.97E-02	0.307345	68.85
Operator	4.90E-02	0.252225	56.50
Operator*Part	3.41E-02	0.175623	39.34
Part-To-Part	3.03E-02	0.155806	34.90
Total Variation	8.67E-02	0.446408	100.00

Number of Distinct Categories = 1

Gage R&R for FAROS25.44

FAROS25.44

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:



Gage R&R Study - ANOVA Method

Gage R&R for FAROS38.03

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0086276	0.0009586	14.0674	0.00000
Operator	2	0.0023221	0.0011610	17.0378	0.00007
Operator*Part	18	0.0012266	0.0000681	1.2751	0.23682
Repeatability	60	0.0032067	0.0000534		
Total	89	0.0153829			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	9.48E-05	48.92
Repeatability	5.34E-05	27.59
Reproducibility	4.13E-05	21.34
Operator	3.64E-05	18.81
Operator*Part	4.90E-06	2.53
Part-To-Part	9.89E-05	51.08
Total Variation	1.94E-04	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	9.74E-03	5.01E-02	69.95
Repeatability	7.31E-03	3.76E-02	52.53
Reproducibility	6.43E-03	3.31E-02	46.19
Operator	6.04E-03	3.11E-02	43.37
Operator*Part	2.21E-03	1.14E-02	15.90
Part-To-Part	9.95E-03	5.12E-02	71.47
Total Variation	1.39E-02	7.17E-02	100.00

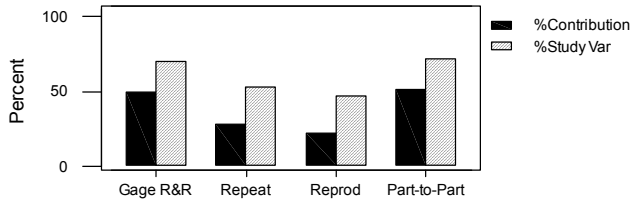
Number of Distinct Categories = 1

Gage R&R for FAROS38.03

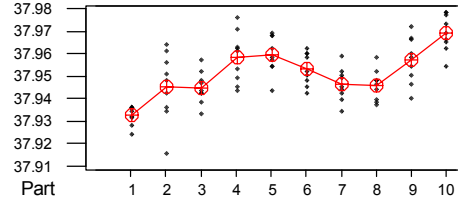
FAROS38.03

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:

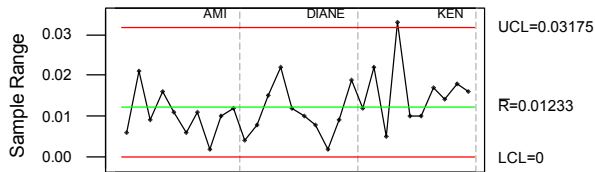
Components of Variation



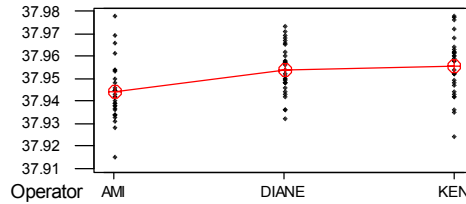
By Part



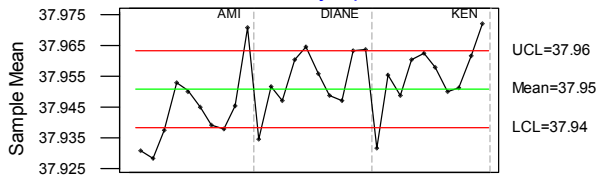
R Chart by Operator



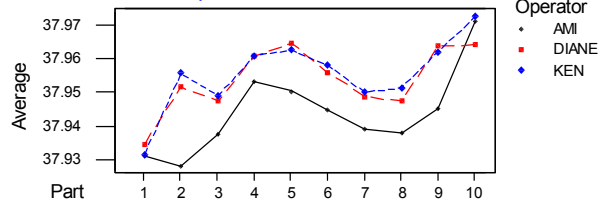
By Operator



Xbar Chart by Operator



Operator*Part Interaction



Operator
• AMI
■ DIANE
◆ KEN

Gage R&R Study - ANOVA Method

Gage R&R for FAROS40.34

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0215558	0.0023951	383.328	0.00000
Operator	2	0.0002164	0.0001082	17.319	0.00006
Operator*Part	18	0.0001125	0.0000062	1.345	0.19404
Repeatability	60	0.0002787	0.0000046		
Total	89	0.0221634			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	8.58E-06	3.13
Repeatability	4.64E-06	1.70
Reproducibility	3.93E-06	1.44
Operator	3.40E-06	1.24
Operator*Part	5.35E-07	0.20
Part-To-Part	2.65E-04	96.87
Total Variation	2.74E-04	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	2.93E-03	1.51E-02	17.69
Repeatability	2.16E-03	1.11E-02	13.02
Reproducibility	1.98E-03	1.02E-02	11.98
Operator	1.84E-03	9.49E-03	11.14
Operator*Part	7.31E-04	3.77E-03	4.42
Part-To-Part	1.63E-02	8.39E-02	98.42
Total Variation	1.66E-02	8.52E-02	100.00

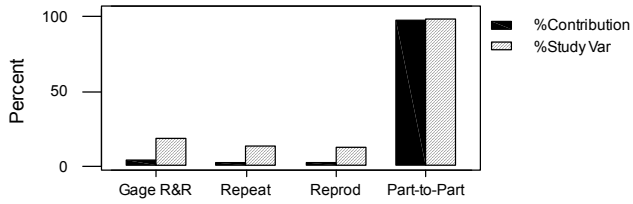
Number of Distinct Categories = 8

Gage R&R for FAROS40.34

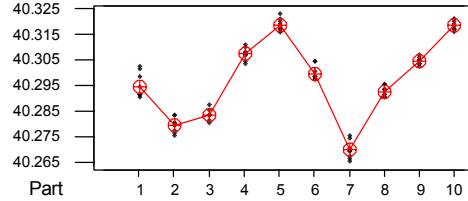
FAROS40.34

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:

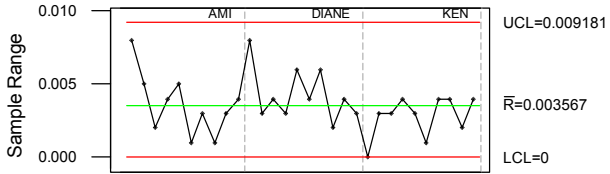
Components of Variation



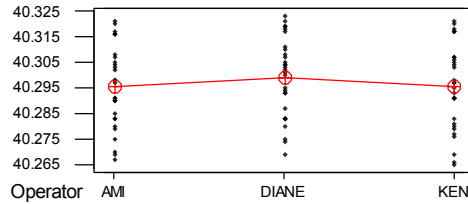
By Part



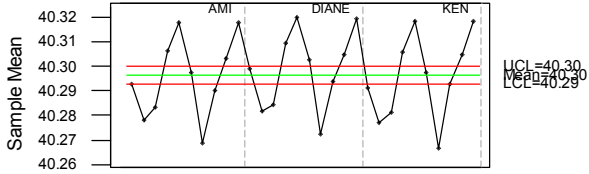
R Chart by Operator



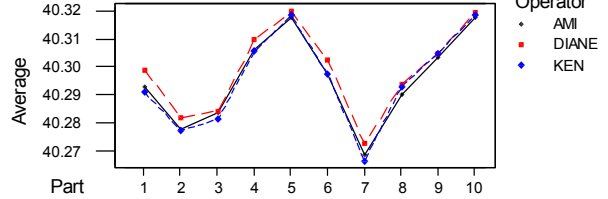
By Operator



Xbar Chart by Operator



Operator*Part Interaction



Gage R&R Study - ANOVA Method

Gage R&R for FAROS1.63b

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.090921	0.0101024	6.87999	0.00027
Operator	2	0.029278	0.0146392	9.96972	0.00122
Operator*Part	18	0.026431	0.0014684	6.21751	0.00000
Repeatability	60	0.014170	0.0002362		
Total	89	0.160800			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	1.09E-03	53.09
Repeatability	2.36E-04	11.55
Reproducibility	8.50E-04	41.55
Operator	4.39E-04	21.47
Operator*Part	4.11E-04	20.08
Part-To-Part	9.59E-04	46.91
Total Variation	2.05E-03	100.00

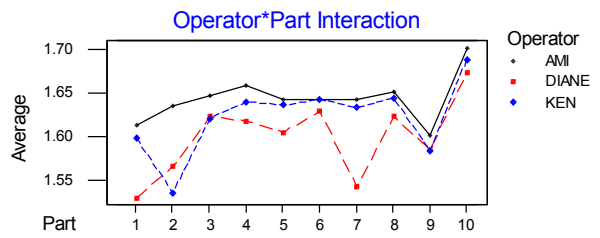
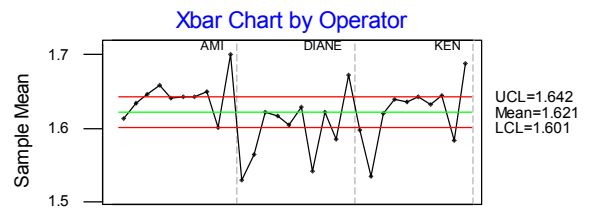
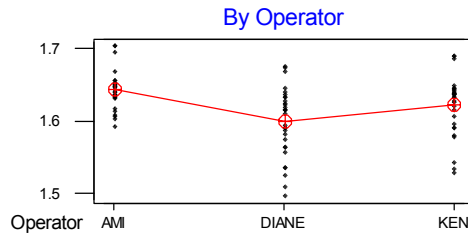
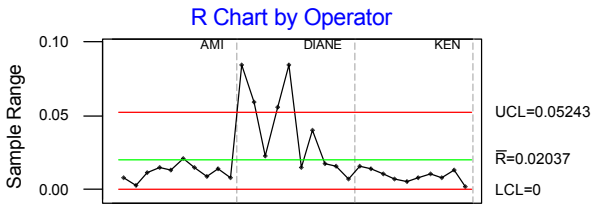
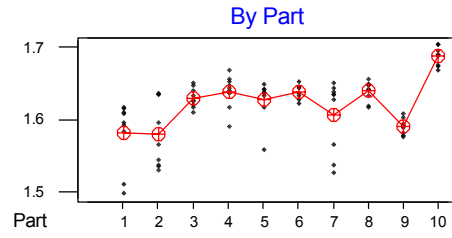
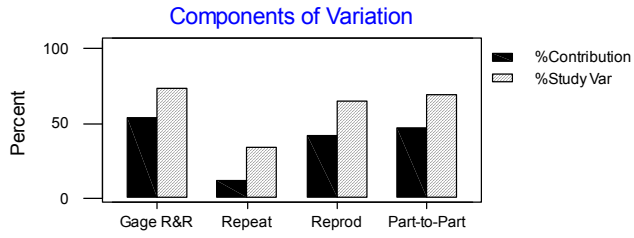
Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	3.30E-02	0.169710	72.87
Repeatability	1.54E-02	0.079144	33.98
Reproducibility	2.92E-02	0.150126	64.46
Operator	2.10E-02	0.107908	46.33
Operator*Part	2.03E-02	0.104373	44.81
Part-To-Part	3.10E-02	0.159511	68.49
Total Variation	4.52E-02	0.232907	100.00

Number of Distinct Categories = 1

Gage R&R for FAROS1.63b

FAROS1.63b

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:



Gage R&R Study - ANOVA Method

Gage R&R for FAROS1.00

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0311078	0.0034564	99.7507	0.00000
Operator	2	0.0003141	0.0001570	4.5319	0.02547
Operator*Part	18	0.0006237	0.0000347	1.2479	0.25522
Repeatability	60	0.0016660	0.0000278		
Total	89	0.0337116			

Two-Way ANOVA Table Without Interaction

Source	DF	SS	MS	F	P
Part	9	0.0311078	0.0034564	117.745	0.00000
Operator	2	0.0003141	0.0001570	5.349	0.00665
Repeatability	78	0.0022897	0.0000294		
Total	89	0.0337116			

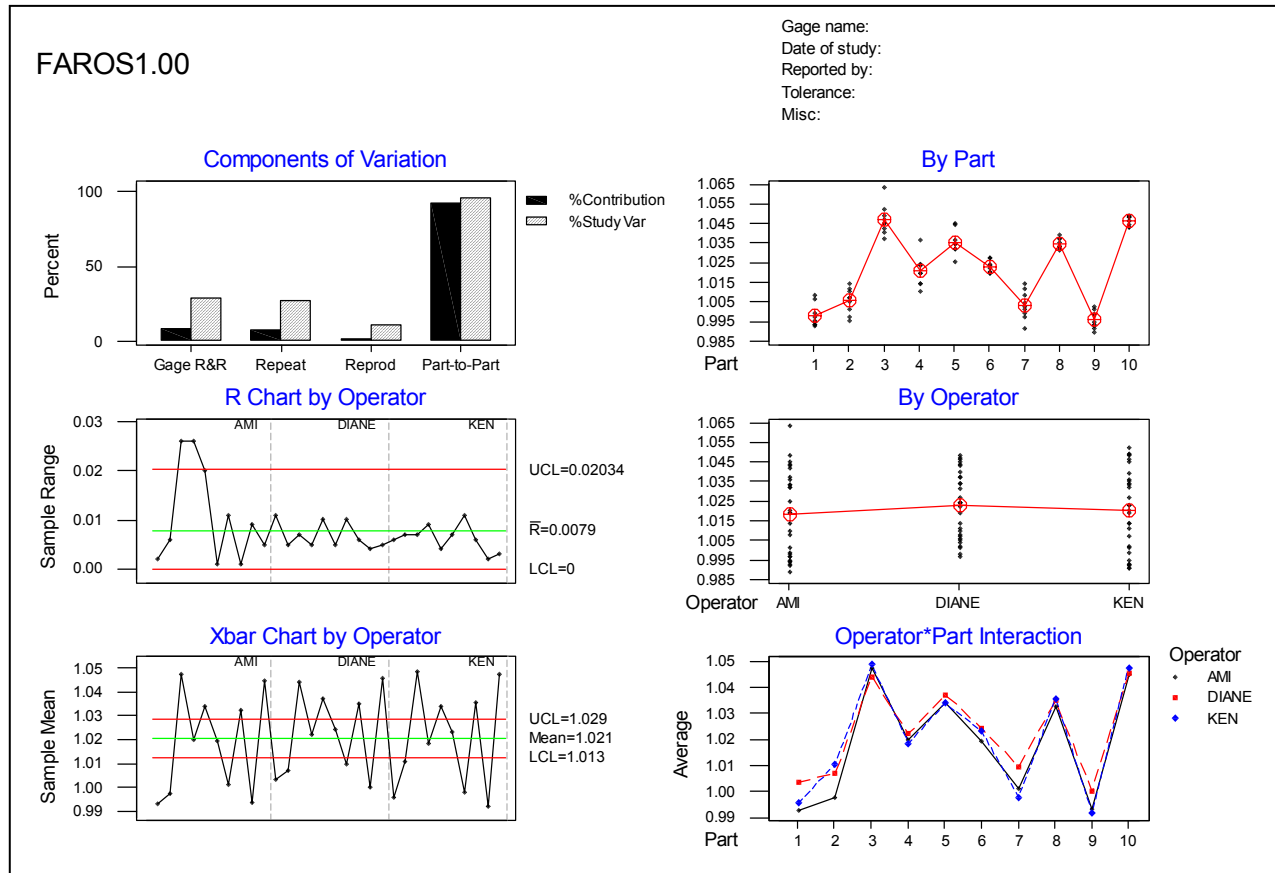
Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	3.36E-05	8.11
Repeatability	2.94E-05	7.08
Reproducibility	4.26E-06	1.03
Operator	4.26E-06	1.03
Part-To-Part	3.81E-04	91.89
Total Variation	4.14E-04	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	5.80E-03	0.029857	28.48
Repeatability	5.42E-03	0.027903	26.62
Reproducibility	2.06E-03	0.010624	10.13
Operator	2.06E-03	0.010624	10.13
Part-To-Part	1.95E-02	0.100496	95.86
Total Variation	2.04E-02	0.104837	100.00

Number of Distinct Categories = 5

Gage R&R for FAROS1.00



Gage R&R Study - ANOVA Method

Gage R&R for FAROS2.91

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0663248	0.0073694	179.531	0.00000
Operator	2	0.0000607	0.0000303	0.739	0.49142
Operator*Part	18	0.0007389	0.0000410	1.619	0.08407
Repeatability	60	0.0015213	0.0000254		
Total	89	0.0686457			

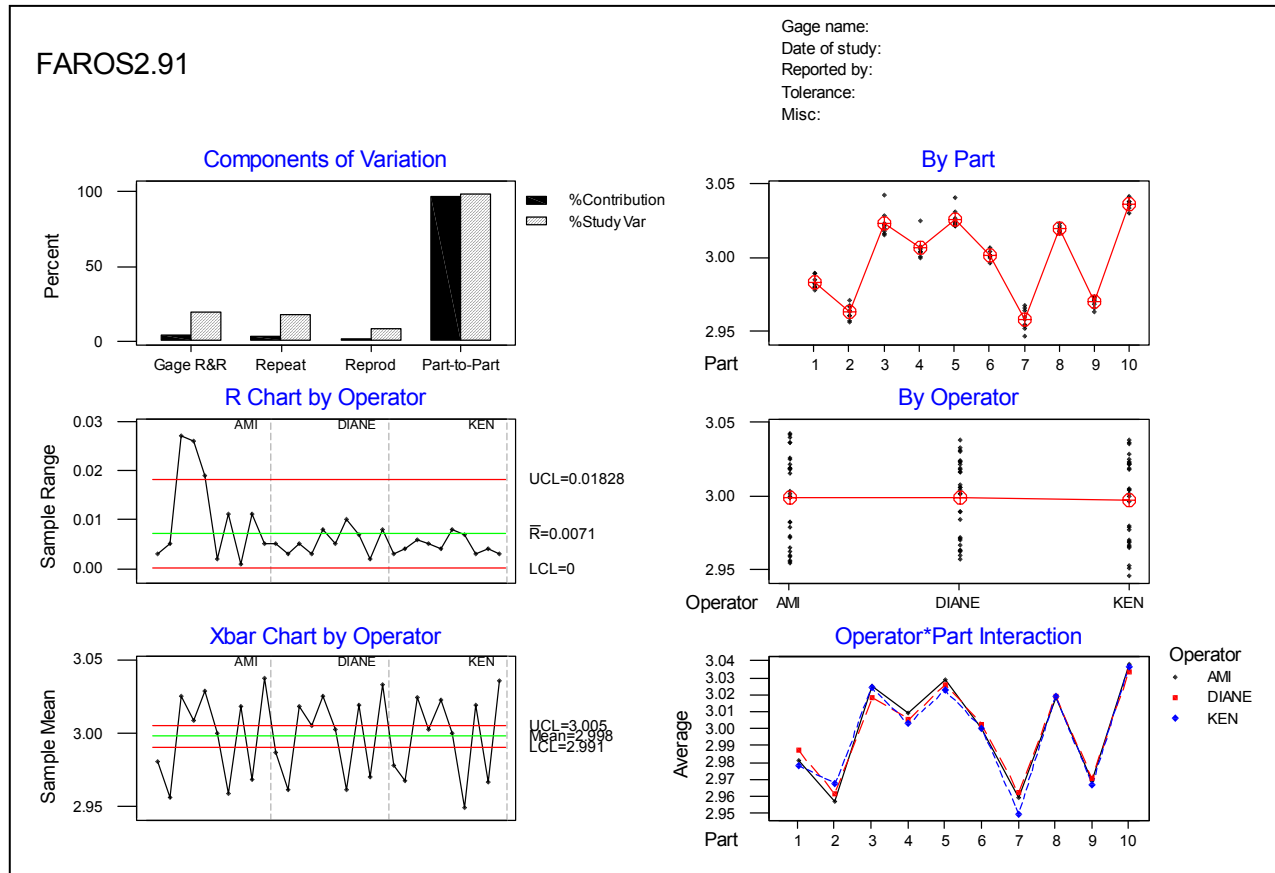
Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	3.06E-05	3.62
Repeatability	2.54E-05	3.00
Reproducibility	5.23E-06	0.62
Operator	0.00E+00	0.00
Operator*Part	5.23E-06	0.62
Part-To-Part	8.14E-04	96.38
Total Variation	8.45E-04	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	5.53E-03	0.028482	19.03
Repeatability	5.04E-03	0.025932	17.32
Reproducibility	2.29E-03	0.011779	7.87
Operator	0.00E+00	0.000000	0.00
Operator*Part	2.29E-03	0.011779	7.87
Part-To-Part	2.85E-02	0.146957	98.17
Total Variation	2.91E-02	0.149691	100.00

Number of Distinct Categories = 7

Gage R&R for FAROS2.91



Gage R&R Study - ANOVA Method

Gage R&R for FAROS40.1

```
** Error ** No variation within part/operator subgroups;  
execution aborted.
```

Gage R&R Study - ANOVA Method

Gage R&R for FAROS145

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.204556	0.0227284	2.06159	0.09151
Operator	2	0.146000	0.0730000	6.62150	0.00699
Operator*Part	18	0.198444	0.0110247	1.94553	0.02855
Repeatability	60	0.340000	0.0056667		
Total	89	0.889000			

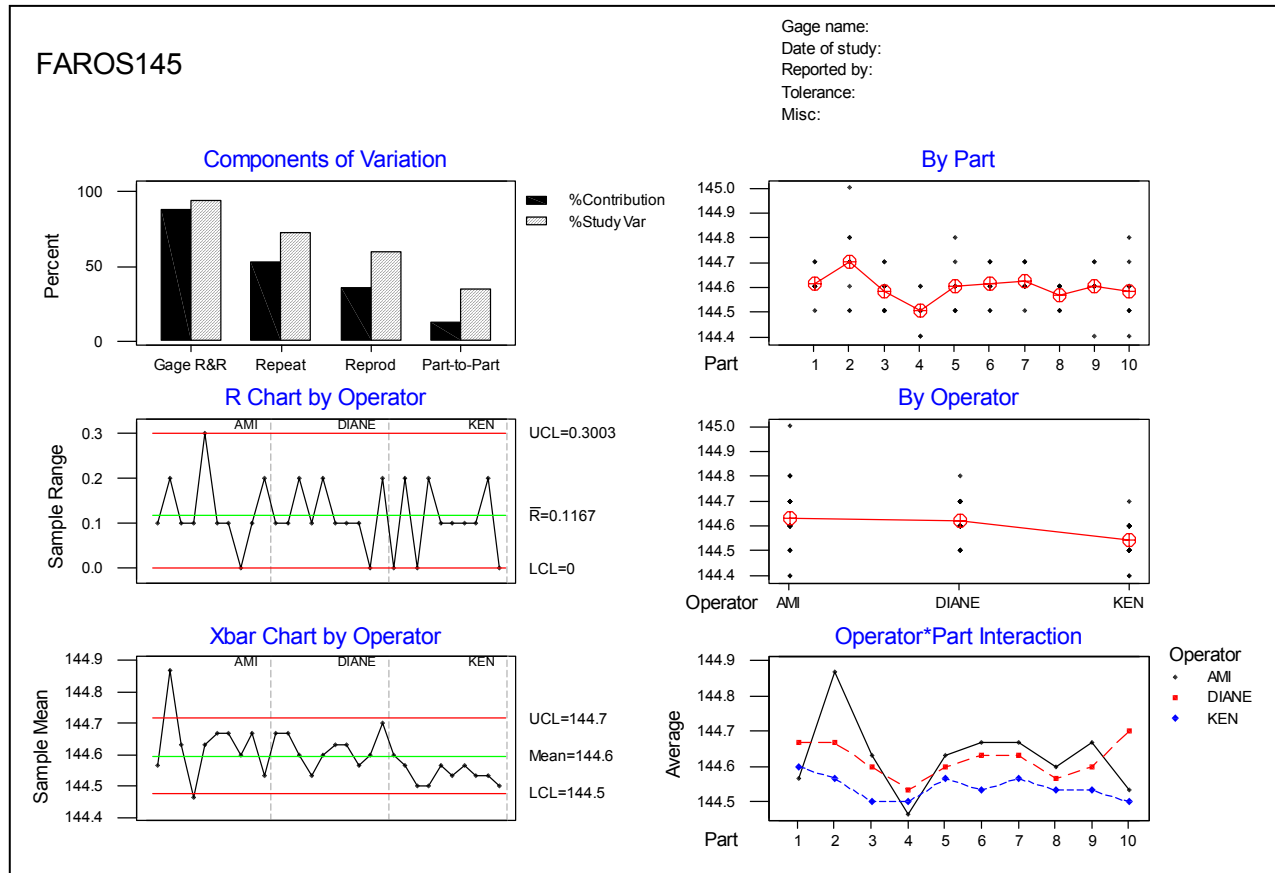
Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.009519	87.98
Repeatability	0.005667	52.38
Reproducibility	0.003852	35.60
Operator	0.002066	19.09
Operator*Part	0.001786	16.51
Part-To-Part	0.001300	12.02
Total Variation	0.010819	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	0.097563	0.502449	93.80
Repeatability	0.075277	0.387678	72.37
Reproducibility	0.062063	0.319626	59.67
Operator	0.045452	0.234075	43.70
Operator*Part	0.042261	0.217645	40.63
Part-To-Part	0.036061	0.185715	34.67
Total Variation	0.104014	0.535673	100.00

Number of Distinct Categories = 1

Gage R&R for FAROS145



Gage R&R Study - ANOVA Method

Gage R&R for FAROS13.78

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part	9	0.0147758	0.0016418	159.012	0.00000
Operator	2	0.0000626	0.0000313	3.032	0.07333
Operator*Part	18	0.0001858	0.0000103	1.063	0.40928
Repeatability	60	0.0005827	0.0000097		
Total	89	0.0156069			

Two-Way ANOVA Table Without Interaction

Source	DF	SS	MS	F	P
Part	9	0.0147758	0.0016418	166.630	0.00000
Operator	2	0.0000626	0.0000313	3.177	0.04717
Repeatability	78	0.0007685	0.0000099		
Total	89	0.0156069			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	1.06E-05	5.51
Repeatability	9.85E-06	5.13
Reproducibility	7.15E-07	0.37
Operator	7.15E-07	0.37
Part-To-Part	1.81E-04	94.49
Total Variation	1.92E-04	100.00

Source	StdDev (SD)	Study Var (5.15*SD)	%Study Var (%SV)
Total Gage R&R	3.25E-03	1.67E-02	23.47
Repeatability	3.14E-03	1.62E-02	22.66
Reproducibility	8.46E-04	4.35E-03	6.10
Operator	8.46E-04	4.35E-03	6.10
Part-To-Part	1.35E-02	6.93E-02	97.21
Total Variation	1.39E-02	7.13E-02	100.00

Number of Distinct Categories = 6

Gage R&R for FAROS13.78

FAROS13.78

Gage name:
Date of study:
Reported by:
Tolerance:
Misc:

