Measurement System Analysis for Quality Improvement

Using Gage R&R Study at Company XYZ

By

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ABSTRACT

Measurement method is the first step of production control and quality improvement because operators need precise and accurate data for analyzing and solving problems. Gage R&R is a process to check tools, equipments, or operators if they are nonconforming. Results of Gage R&R can define causes of the measurement errors. After analyzing the results, the measurement system will be more precise and more accurate.

Company XYZ is a high quality float glass manufacturer in Wisconsin. They have flexible capabilities to produce a variety dimension of glass. Two years ago, the company received complaints from customers regarding the quality of the glass and that it did not meet their expectations. One response was that the company installed a new digital measuring table to solve the problem. Unfortunately the measurement table could not solve this problem.

The purposes of this study were to determine if the measurement system could produce precise and accurate data, and if the precision and accuracy could solve the complaint problems by proving the measurement data to the customer. In addition, this study could evaluate the reliability of the measurement system that the manufacturing plant had recently applied in their production process.

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Chapter I: Introduction

Currently, the manufacturing industry faces difficult competition. Competition has increased because of increased customer demands. The manufacturing industry has to actively perform improvement in order to improve their customers' satisfactions. Chua, Defro, & Gryna (2007) said even though most of manufacturing industries focus on improving the quality of products in order to enhance their customers' satisfaction, the productivity is not achieved because of the errors in measurement system. The measurement errors occur from variations of instruments, measurement methods, and operators (Montgomery, 2005). In order to improve productivity, the companies should calibrate their instruments and measurement method before operating inspection to achieve precise and accurate data.

Measurement method is the first step of production control and quality improvement because operators need precise and accurate data for analyzing and solving problems (Montgomery, 2005). According to Spitzer (2007), quality expert Kames Harrington has said:

> Measurement is the first step that leads to control and eventually to improvement. If you can't measure something, you can't understand it. If you can't understand it, you can't control it. If you can't control it, you can't improve it.

Gage Reliability and Reproducibility (Gage R&R), a kind of Measurement System Analysis (MSA), is an important step before analyzing the measurement data. It is a process to check tools, equipments, or operators if they are nonconforming. Results of Gage R&R can define causes of the measurement errors. After analyzing the results, the measurement system will be more precise and more accurate (Montgomery, 2005).

Company XYZ is a high quality float glass manufacturer in Wisconsin. The company runs 24 hours a day, 365 days a year. This company also has flexible capabilities to produce a variety of thicknesses in glass, ranging from 1.6 mm to 7.0 mm, required for the residential market. The float glass pieces are made from eight different raw materials such as sand, limestone, soda ash, dolomite, salt cake, Nepheline Syenite, rouge, and carbon, with a precise formulation. The precise formulation is mixed in the batch house and then conveyed to the batch hopper where it is uniformly loaded into the furnace.

During the melting process, gases are released as the raw materials become molten. The hot spot in the melter is maintained at approximately 2,900°F. The tweel is a refractory gate that controls the flow of molten glass from the working end of the furnace to the tin bath. The molten glass flows through a channel called the canal before it enters the tin bath at approximately 2,000°F. The tin bath is the key to modern float glass technology, as the molten glass actually floats on top of 2 inches of molten tin. The molten glass continues its flow, exiting the bath at an approximate temperature of 1,150°F.

Top roll machines are used to precisely control the width and thickness of the molten glass during the forming process in the tin bath. The tin bath chamber uses an atmosphere of 92% nitrogen and 8% hydrogen to prevent oxidation. The combination of this environment and temperature allows the glass to achieve a natural fire polished finish. An annealing chamber uses electric heat and radiant cooling to gradually lower the glass temperature in a uniform manner. The entire cooling process is controlled to create the proper inherent strength of the glass, while maximizing the ability to cut the finished product (Lau, 2006).

A thickness gauge measures thickness, determining if any portion is out of spec. A camera inspection system focuses on edge quality and squareness, to ensure that the edges meet the specification. Lasers are used to locate any defects and feed their location to the cold end control computer for marking. The laser system inspects the quality of the entire glass so that customers feel confident when purchasing the glass.

Statement of the Problem

Two years ago, the company received complaints from customers regarding the quality of the glass and that it did not meet their expectations. The glass pieces were either too small or too big that the customers received. Normally the Company XYZ inspected all dimensions of their products before shipping. The quality manager called all related people to solve this problem. Six months later, the quality manager added a measurement device, a digital measurement table, into the production line. This measurement table measured the width dimension with high precision and accuracy. In addition, it also electronically recorded measurement data at the same time. When an operator measured a piece of glass, the measurement data was gathered by a computer into a data collection sheet file. The cost of the digital measurement table was $40,000.

Unfortunately the measurement table could not solve this problem. After adding the table, there were still complaints from one new customer about the wrong size shipping. The new customer complained that they received glass pieces that were both too small and too big glass. The initial analysis by the quality manager stated that the new customer did not have the same measurement method like the other customers because the other customers did not complain about the problem anymore. However, the new customer still mentioned that the problem was XYZ's and wanted them to solve it.

Purpose of the Study

The purposes of this study were to determine if the measurement system could produce precise and accurate data, and if the precision and accuracy could solve the complaint problems by proving the measurement data to the customer. In addition, this study could evaluate the reliability of the measurement system that the manufacturing plant had recently applied in their production processes.

Assumptions of the Study

This study had assumptions as following;

1. The digital measurement table was in good condition and was always calibrated before using.
2. The digital measurement table measured the glass pieces' dimensions precisely and accurately.
3. Operators who perform the inspection were trained well and experienced.
4. The inspections were implemented under normal conditions and same environment.
5. All sample items were mixed both good and bad over the entire specification.
6. All sample items were measured randomly, and the operators could not remember the items when they re-measured them again.
7. The quality manager understood this study and provided everything as needed.
8. Data collecting method was operated correctly, no variation occurred in the system.

Definition of Terms

Accuracy. The degree to which a measurement system is accurate will generally be the difference between an observed average measurement and the associated known standard value (George, Maxey, Price, & Rowlands, 2005).

ANOVA. Analysis of the variance. A statistical method that tests contribution of control factors and interactive effects between the different factors (Levine, 2006).

Calibrate. To standardize an instrument for being ready measuring (DeCarlo, Gygi, & Williams 2005).

Defect. A fault or a lack of something that makes something not perfect (Montgomery, 2005).

Gage. An instrument that measures the amount or size of something (Montgomery, 2005).

Gage R&R. Gage Repeatability and Reproducibility. A statistical tool that measures the amount of the variation seen within the instrument and the variation between the various appraisers (George, Maxey, Price, & Rowlands, 2005).

Inspection. The process of carefully checking an object's condition, performance, or characteristic during product development or manufacturing (Creveling, Hambleton, & McCarthy, 2006).

Measurement error. The fault in a measurement data set occurring from variation in the measurement system (Creveling, Hambleton, & McCarthy, 2006).

Measurement data. Collected data showing a characteristic of an item, product, process, or thing (Levine, 2006).

MINITAB. A general purpose statistical software package used to manipulate and examine data easily, including facilities to plot and tabulate data (DeCarlo, Gygi, & Williams 2005).

Process Capability. The ability of a process to maintain product characteristics within present limit (Montgomery, 2005).

Repeatability. Variation in the averages from repeated measurement of the same item (Creveling, Hambleton, & McCarthy, 2006).

Reproducibility. Variation in the repeated measurement made by different people on the same item (Creveling, Hambleton, & McCarthy, 2006).

Sample. A small part or amount of something that is examined or used in order to find out what the test looks like (Levine, 2006).

SPC. Statistical Process Control. A problem solving tool that may be applied to any process (Montgomery, 2005).

Variation. A difference or change from the usual amount or form of something due to systematic or random effects (Creveling, Hambleton, & McCarthy, 2006).

Limitations of Study

This study was limited by work experience and available time of the researcher.

Methodology

This Gage R&R study was to evaluate the measurement systems. This methodology would explain how to implement the Gage R&R study. According to the Automotive Industry Action Group (AIAG) standards, the long testing form required three operators measuring 10 items in three times (George, Maxey, Price, & Rowlands, 2005). All inspections had to be measured under conditions of the same instrument, same setup, same environmental condition, and the sample items had the same characteristics. Each operator had to measure each sample item three times in random sequence (George, 2005). For evaluating the repeatability of the measurement system, the operator was the same person. Then the measurement data would be gathered automatically by a computer. The measurement data would be entered in a software program, MINITAB, and analyzed by the Analysis of the Variance (ANOVA) method (Wang, 2004). Final step, the results would be assessing the capability of the measurement system. The researcher and the quality manager would make recommendations for improvement.

Chapter II: Literature Review

Organizations often fail to notice the impact of not having quality measurement systems (Breyfogle, 2003). A good part can be rejected erroneously, a bad part can be accepted mistakenly, or a satisfactory process can appear unsatisfactory. All this can lead to lost sales and profits and unnecessary expense gained while trying to fix a manufacturing or business process when the primary source of variability actually arises from the measurement system. According to Kappele & Raffaldi (2006), to achieve precise and accurate data for making a right decision, we have to have precision instruments, suitable measurement methods, and skillful appraisers.

Measurement system is an important factor for evaluating your performance systems. It is the inclusive process of obtaining measurements including instruments, people, methods, and operations. Measurement system analysis can evaluate the measurement system which is in use if it is capable of making accurate and reliable measurements for decision making. Measurement analysis concentrates on costs of process, and it may take long time before getting back the benefit which is more valuable than the costs. Mukherjee, Paul, & Roy (2005) stated that it may not be cost efficient to calibrate each measurement device every day, nor would it be good practice to calibrate or test each device only once per decade. An instrument which is not calibrated frequently may fall out of specification, and quality of product will be weakened. In addition to calibrating an instrument, a Gage R&R study must be conducted to evaluate the system's reliability.

Measurement System Analysis

Montgomery (2005) defined that the Measurement System Analysis (MSA) is an experimental and statistical method that identifies the variations in the measurement system. It is used to confirm that the differences in the data are due to actual differences in what is being measured and not to variation in measurement methods. The purpose of MSA is to determine if a measurement system can generate accurate data, and if the accuracy is adequate to achieve objectives. According to Breyfogle (2003), possible sources of variation can be discovered by analyzing linearity, stability, repeatability, and reproducibility of the measurement system.

Bias. It is the term given to the difference between the observed average of measurement and the reference or master value (Pyzdek, 2003). The reference value can be calculated from the average value of all measurements. Bias is the systematic error that is an indication of a measuring instrument. It is evaluated and expressed at a single point within the operating range of the measurement system. In terms of statistics, bias can be recognized when the averages of measurements have a different fixed amount from the reference value (George, Maxey, Price & Rowlands, 2005).

Linearity. It can be determined when you measure the reference or master value with known characteristics values repeatedly. The amount of difference throughout the measurement range is the linearity. It can also be the amount of deviation from a normal performance of instrument. (George, Maxey, Price, & Rowlands, 2005).

Stability. This is the total variation in the measurements occurred when you measure the same master or parts with a single characteristic over an extended time period (George, Maxey, Price, & Rowlands, 2005). Pyzdek (2003) referred stability to as drift. If measurements do not change or drift over time, the instrument is considered to be stable. Stability of the measurement system can be tested by maintaining a control chart on the measurement system.

Repeatability. This is the basic natural precision of the gage. It is the variability in measurements that occurs when consecutive measurements are made with one measurement instrument. The measurements are operated several times by a fixed appraiser while measuring the identical characteristic on the same part. It is also commonly known as equipment variation (George, Maxey, Price, & Rowlands, 2005).

Reproducibility. This is the variability due to different operators using the gage in repeated measurement. The appraisers use the same instrument while measuring the identical characteristic on the same part. It is commonly known as appraiser variation (George, Maxey, Price, & Rowlands, 2005).

Measurement Error

The measurement error is the estimated amount that a measured value is different from its reference or master value. According to Mukherjee, Paul, & Roy (2005), measurement errors can be occurred from equipments, operators, test designs and various other factors. Many are difficult to identify and quantify. To increase the accuracy of measurements, the measurement errors must be minimized. In order to develop uncertainty statements, suspected measurement errors are assigned estimated probability values (Creveling, Hambleton, & McCarthy, 2006).

It can never be certain that the measured value of a reading is the correct value. Measurement readings are estimates of true values. Measurement uncertainty may be defined as the probability that a reading will fall in the interval that contains the reference value. Normally, it can be divided into two categories: precision and accuracy. The difference between accuracy and precision is accuracy describes the variation between the measurement and the reference value, but precision describes the variation when you measure the same part repeatedly with the same instrument (Creveling, Hambleton, & McCarthy, 2006).

Precision. DeCarlo, Gygi, & Williams (2005) defined precision is a characteristic of measurement methods or measurement devices. In other words, the precision in a measurement system can be evaluated by assessing variations. The variations occur when measurements are repeated with the same instrument, appraiser, and measurement method on the same part. If the measurement data are not showing any evident difference, the measurement system is very precise as shown in figure 1a.

Accuracy. It is an ability of measurement system to get the measured value close to the reference value when you repeat a measurement as shown in figure 1c (DeCarlo, Gygi, & Williams 2005). In figure 1c, the measurement data are grouped very close to the center which is the reference value, but the measurement data are not precise because they spread out around the center. In figure 1b, the measurement data are in the same location but they are not close to the center which means that they are not precise. In case of repeated measurement, the reference value can be calculated from the average value of all measurements.

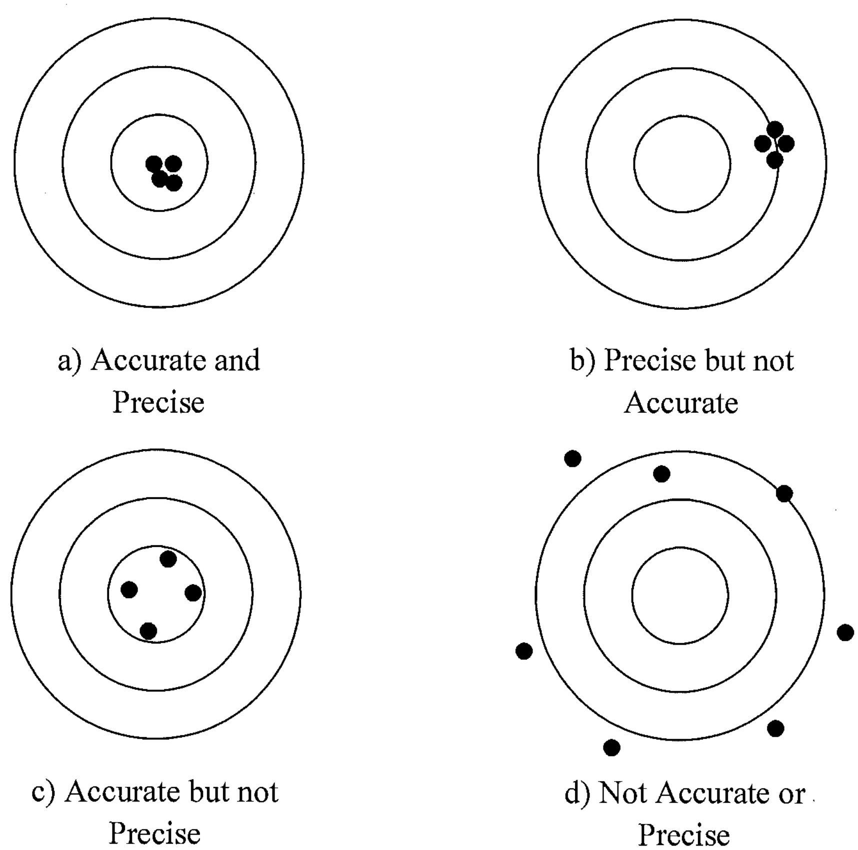

Figure 1. Precision and Accuracy (DeCarlo, Gygi, & Williams 2005)

Within any measurement system, there may be one or both problems of precision and accuracy as shown in figure 1d. For an example, you can have a tool which measures parts precisely but not accurately. On the other hand, you can have a tool that is accurate, but not precise, that is, the measurements have large variance. However, you can have a tool that is neither accurate nor precise (DeCarlo, Gygi, & Williams 2005).

Variation

It is a difference or change from the usual amount or form of something. In addition to the objects that are measured, the measuring instrument has variability in itself. Two different instruments may measure the same part and provide different results. In many cases, measuring parts in the second time with the same instrument will give a different result. A low value of the instrument's standard deviation indicates greater precision. When an instrument is accurate but not precise, the measurements are distributed around the reference value within the acceptable range (figure 1c). When an instrument is precise but not accurate, the measurements are grouped close together but at a distance from the reference value (figure 1b). When an instrument is both accurate and precise, the data are clustered close together around the reference value (figure 1a) (DeCarlo, Gygi, & Williams 2005). Possible causes of variation in a measurement system include part-to-part and measurement system. Part-to-part variation is an estimate of variation between the parts being measured. Measurement system variation can occur from instruments, measurement methods, operators, and various other factors (Wang, 2004).

Control Charts

A control chart is a statistical tool used as a tool to continuously monitor and make adjustments to the product or process. It is also used to distinguish between variation in a process resulting from common causes and variation resulting from special causes. In addition, control charts are a means of graphing variation patterns from process or product characteristics so that corrective action may be taken if required. It presents a graphic display of process stability or instability over time, not performance (Montgomery, 2005).

Montgomery (2005) described that the control chart distinguishes between normal and non-normal variation through the use of statistical tests and control limits. The control limits are calculated using the rules of probability so that when a point is determined to be out of control, it is due to an assignable cause and not due to normal variation. Points outside the control limits are not the only criteria to determine out of control conditions. All points may be inside the limits and the process may still be out of control if it does not display a normal pattern of variation. Zone tests are used to determine out of control conditions. Zone tests are hypothesis tests in a modified form. They are used to test if the plotted points are following a normal pattern of variation.

Control charts were one of the first statistical techniques introduced in statistical quality control. Dr. Walter A. Shewhart of AT&T Bell Laboratories developed the charts in 1924. The original charts for variables data, x bar and R charts, were called Shewhart charts. Currently, the purpose of the control chart is to indicate whether or not a process is in statistical control. Statistical control means that the plotted points follow a pattern of variation consistent with the areas under the normal curve. There are two types of control charts: the variables control chart and the attributes control chart. The variables charts use actual measurements as data and the attribute charts use percentages or counts (Montgomery, 2005).

Gage Repeatability and Reproducibility

Gage repeatability and reproducibility (R&R) study involves breaking the total gage variability into two portions: repeatability and reproducibility. Gage R&R study is used to measure the amount of variation in an observed process. It is due to measurement system variation and breaks down the measurement system variation into repeatability and reproducibility. There are two most common method types used and supported by statistical software: average and range method and analysis of the variance. The difference between the two methods is the methodologies to calculate them (Levine, 2006).

Average and Range method. According to Levine (2006), the Average and Range method is quite simple to use in that it avoids a lot of complicated calculation and can be run by hand. The Average and Range method is a method used to conduct Gage R&R. It involves finding the average measurements of parts and operators, then finding the range of results from the parts and operators.

Analysis of the variance. The ANOVA is more complicated. It can test contribution of control factors and interactive effects between the different factors. The ANOVA can be extended to analyze the data from an experiment and to estimate the appropriate components of gage variability. The technique finds the sum of squared distances of results from the overall average, the average of operators and parts to assess where variation is found. This will then show how many variations are found in the measurements from parts, operators, and also interactions between parts and operator (Levine, 2006).

A big difference between the two methods is that the Average and Range method will not show interactions between how operators measure parts, but the ANOVA will show this (Wang, 2004). The Average and Range method breaks down the overall variation into three categories: part-to-part, repeatability, and reproducibility (figure 2). In order to compare to ANOVA, the ANOVA method goes one step further and breaks down reproducibility into its operator, and operator-by-part, components. Wang (2004) stated that generally the results getting from both methods should be similar.

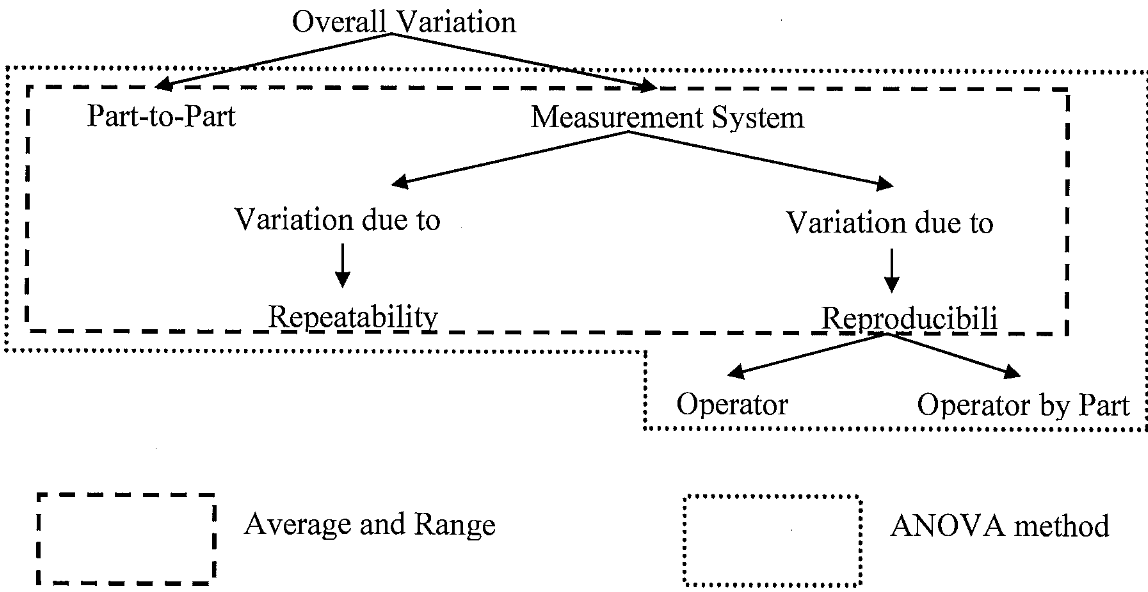

Figure 2. Gage R&R methodologies (Wang, 2004)

An operator effect can best be described as a Bias between operators, an interaction could be where some parts are measured precisely, yet others are measured with a very different result between operators. For an example, interactions imply you have to start asking why do the operators get similar results for the second part, yet when they measure the fifth part "operator A" measures higher than "operator B", and the sixth part "operator A" records very low results. Interactions may imply difficulties in measuring certain parts, such as non uniform parts, or could imply other problems (Montgomery, 2005).

Chapter III: Methodology

The statement of this research problem was the Company XYZ received complaints from one new customer regarding the quality of the glass and that it did not meet their expectations. The glass pieces were both too small and too large that the customers received. As a result, customers believed that the measurement system of the company XYZ was unreliable. One response was that the company installed a new digital measuring table to solve the problem. The quality manager wanted to determine how well the new system measures the glass. After interpreting the measurement data, the researcher determined if the measurement system could produce precise and accurate data, and if the precision and accuracy could solve the problem by proving the accuracy of the measurement data to the customers. This chapter discusses the methodology applied to gather and analyze the data in this research study.

Instrumentation

As part of the inspection process, there was a digital measurement table used to measure the dimension of the various pieces of glass. This measurement table measured the width dimension with high precision and accuracy. In addition, it also electronically recorded measurement data at the same time. When an operator measured a piece of glass, the measurement data was gathered by a computer into a data collection sheet file. The data collection sheet was designed by the researcher to easy compile the measurement data. Then, the data was entered in a software program, MINITAB version 15, and analyzed using ANOVA. The MINITAB software measured percentage of contribution on the variance components as repeatability, reproducibility, and part-to-part.

Data Collection Procedures

According to the Automotive Industry Action Group (AIAG) standards, the long testing form requires three operators measuring 10 items in three times (George, Maxey, Price, & Rowlands, 2005). The testing was done using two different sizes of glass, 24 inches and 48 inches. In testing each size, the quality manager randomly sampled 10 good and bad pieces of glass products across all major sources of process variation that represent those typically produced. The pieces of glass were identified by assessing a number. It was placed on their backsides so the researcher and observer would not be confused in the sequencing. The first operator measured the 10 pieces of glass in random order. Then, the second and third operator measured the 10 pieces of glass in a different random order respectively as shown in figure 3. Each operator repeated the process on the same 10 pieces three times, for a total of 90 measurements in each size. All inspections were measured under conditions of the same instrument, same setup, same environmental condition, and the sample items had to have the same characteristics. The measurement data was gathered by a computer into a data collection sheet file. No information about specific operators was gathered. When the researcher received the measurement data, the data was entered in the MINITAB, and analyzed using ANOVA. The result of analysis assessed the capability of the measurement system.

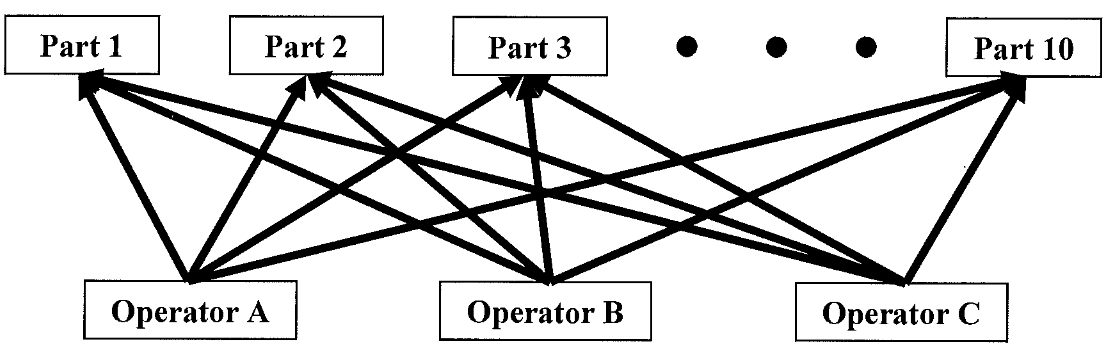

Figure 3. Gage R&R procedures

Data Analysis

At the core of any successful quality control process is a statistical tool that is powerful, reliable, and easy to use. MINITAB is one of the statistical software which has been used by many successful companies in their deployment of quality control functions. This study was analyzed by using MINITAB software to evaluate repeatability and reproducibility of the measurement system. The data would be interpreted in form of percentage of contribution on the variance components. The percentage of contribution would be accepted if it was fewer than 10%. If it was between 10% and 30%, the measurement system may be acceptable depending on importance of application, cost of repairs or cost of gage, etc. If it was over than 30%, the measurement system was not satisfactory and it needed improvement (Measurement Systems Analysis Reference Manual, 1995). This research would be finished when the researcher could affirm that the measurement system could produce precise and accurate data or not. If the measurement system did not produce precise and accurate data, the analyst method could propose the causes of the problem.

Chapter IV: Results

The purposes of this study, as mentioned in Chapter 1, were to determine if the measurement system could produce precise and accurate data, and if the precision and accuracy could solve the complaint problems by proving the measurement data to the customer. In addition, this study could evaluate the reliability of the measurement system that the manufacturing plant had recently applied in their production processes. This evaluation would be provided to the customer to show the measurement system performance of the Company XYZ.

Gage R&R study provided information on measurement system performance by analyzing measurement error from various sources. If a large amount of variability was presented in a measurement system, this could lead to poor quality product being shipped to customers by not being able to use the measurement system to differentiate between conforming and nonconforming parts. While determining if a measurement system was reliable, the sources of measurement variations were broken into three categories: part-to-part, repeatability or equipment, and reproducibility or appraiser. Process control and quality control processes were used to eliminate the variations and make Gage R&R as small as possible relative to the tolerance and the difference between the upper and lower specification limits.

The results of this study were calculated to percentage of total variation. The percentage of total variation was evaluated to determine if the measurement system was acceptable for its intended application. According to Measurement Systems Analysis Reference Manual (1995), guidelines for acceptance of Gage R&R are;

- Under 10% errors – the measurement system is acceptable
- 10% to 30% errors – the measurement system might be acceptable depending on importance of application, cost of repairs or cost of gage, etc.,

- Over 30% errors – measurement system is unacceptable and it needs an improvement. Operators had to make every effort to identify the problems and had them corrected.

Item Analysis

In this section, it describes how the result was and it also shows analysis tables. The first part, table 1-6, uses the average and range method to analyze the measurement data. It shows tables of maximum, minimum, range, and different values. The second part, table 7-13, uses the ANOVA method to show all the results. It also evaluates the measurement system and indentifies which sources of variations causing the measurement errors. The collected data are shown in the Appendix A. These data represented each measurement data of each glass piece in each size. Each piece of glass was measured 10 times by each operator.

Table 1 indicates the maximum and the minimum values of each glass piece for 24 inches measuring three times by each operator. In other words, these values show the variability of repeated measurement of the same part by the same operator in three times repeating.

Table 1

Maximum and minimum of each glass piece for 24 inches

Operator		1	2	3	4	5	6	7	8	9	10
A	Maximum	23.877	23.959	24.018	24.077	24.142	23.883	23.939	23.997	24.063	24.121
A	Minimum	23.874	23.954	24.015	24.076	24.140	23.881	23.937	23.996	24.062	24.119
B	Maximum	23.876	23.959	24.020	24.084	24.146	23.885	23.940	24.001	24.064	24.123
B	Minimum	23.875	23.957	24.019	24.080	24.144	23.883	23.940	23.999	24.062	24.121
C	Maximum	23.874	23.955	24.017	24.077	24.139	23.881	23.937	23.997	24.062	24.119
C	Minimum	23.873	23.955	24.017	24.074	24.138	23.878	23.937	23.994	24.058	24.117

Table 2 indicates the maximum and the minimum values of each glass piece for 48 inches measuring three times by each operator. In other words, these values show the variability of repeated measurement of the same part by the same operator in three times repeating.

Table 2

Maximum and minimum of each glass piece for 48 inches

Operator		1	2	3	4	5	6	7	8	9	10
A	Maximum	47.862	47.928	47.992	47.938	48.133	47.890	47.950	48.014	47.889	48.138
A	Minimum	47.859	47.926	47.991	47.937	48.129	47.886	47.948	48.013	47.888	48.136
B	Maximum	47.865	47.930	47.994	47.939	48.135	47.888	47.950	48.016	47.890	48.137
B	Minimum	47.862	47.927	47.991	47.937	48.131	47.887	47.949	48.014	47.888	48.136
C	Maximum	47.860	47.925	47.992	47.935	48.132	47.887	47.946	48.011	47.888	48.135
C	Minimum	47.859	47.925	47.989	47.934	48.129	47.885	47.945	48.010	47.886	48.132

Table 3 shows the range value of each glass piece for 24 inches measuring three times by each operator. In other words, it shows the variability of reproducibility measurement of the same part by the same operator in three times repeating.

Table 3

Range of each glass piece for 24 inches

Operator		1	2	3	4	5	6	7	8	9	10
A	Range	0.003	0.005	0.003	0.001	0.002	0.002	0.002	0.001	0.001	0.002
B	Range	0.001	0.002	0.001	0.004	0.002	0.002	0	0.002	0.002	0.002
C	Range	0.001	0	0	0.003	0.001	0.003	0	0.003	0.004	0.002

Table 4 shows the range value of each glass piece for 48 inches measuring three times by each operator. In other words, it shows the variability of reproducibility measurement of the same part by the same operator in three times repeating.

Table 4

Range of each glass piece for 48 inches

Operator		1	2	3	4	5	6	7	8	9	10
A	Range	0.003	0.002	0.001	0.001	0.004	0.004	0.002	0.001	0.001	0.002
B	Range	0.003	0.003	0.003	0.002	0.004	0.001	0.001	0.002	0.002	0.001
C	Range	0.001	0	0.003	0.001	0.003	0.002	0.001	0.001	0.002	0.003

As shown in the above tables, there were little variations in each operator which means that the sources of measurement variations were not from operators. Operator 3 performed the best measuring performance.

Table 5 shows the different between the average value of each glass piece measuring three times by each operator and the reference value averaging all measurement data of each part for 24 inches. In other words, it shows the accurate of each operator measuring the same part in three times repeating.

Table 5

Difference between the average value and the reference value for 24 inches

Operator		1	2	3	4	5	6	7	8	9	10
Reference	Average	23.875	23.956	24.018	24.078	24.142	23.882	23.938	23.997	24.062	24.120
A	Average	23.875	23.957	24.016	24.076	24.141	23.882	23.938	23.996	24.062	24.120
B	Average	23.875	23.958	24.020	24.082	24.145	23.884	23.94	24.000	24.063	24.122
C	Average	23.873	23.955	24.017	24.075	24.139	23.88	23.937	23.995	24.060	24.118
A	Difference	0	-0.001	0.002	0.002	0.001	0	0	0.001	0	0
B	Difference	0	-0.002	-0.002	-0.004	-0.003	-0.002	-0.002	-0.003	-0.001	-0.002
C	Difference	0.002	0.001	0.001	0.003	0.003	0.002	0.001	0.002	0.002	0.002

Table 6 shows the different between average value of each glass piece measuring three times by each operator and the reference value averaging all measurement data of each part for 48 inches. In other words, it shows the accurate of each operator measuring the same part in three times repeating.

Table 6

Difference between the average value and the reference value for 48 inches

Operator		1	2	3	4	5	6	7	8	9	10
Reference	Average	47.861	47.927	47.991	47.937	48.432	47.887	47.948	48.013	47.888	48.136
A	Average	47.861	47.927	47.992	47.938	48.131	47.888	47.949	48.013	47.889	48.137
B	Average	47.863	47.928	47.992	47.938	48.133	47.888	47.950	48.015	47.889	48.136
C	Average	47.859	47.925	47.990	47.934	48.130	47.886	47.946	48.011	47.887	48.134
A	Difference	0	0	-0.001	-0.001	0.001	-0.001	-0.001	0	-0.001	-0.001
B	Difference	-0.002	-0.001	-0.001	-0.001	-0.001	-0.001	-0.002	-0.002	-0.001	0
C	Difference	0.002	0.002	0.001	0.003	0.002	0.001	0.002	0.002	0.001	0.002

As shown in the above tables, there were little differences between each average value of each operator and the reference value which means that the measurement system was accuracy. Operator 1 performed the best measuring performance.

Table 7 shows the p-value for 24 inches using ANOVA method in MINITAB. According to MINITAB User's Guide (2000), when the p-value for the Operator*Part is > 0.25, MINITAB passes over this from the full model which means that it fits the model without the interaction.

Table 7

p-value using ANOVA method for 24 inches

Source	DF	SS	MS	F	P
Parts	9	0.536	0.0795262	26303.1	0.000
Operators	2	0.000241	0.0001203	39.8	0.000
Operators * Parts	18	0.000054	0.0000030	2.1	0.015
Repeatability	60	0.000085	0.0000014		
Total	89	0.716116			

Table 8 shows the p-value for 48 inches using ANOVA method in MINITAB.

Table 8

p-value using ANOVA method for 48 inches

Source	DF	SS	MS	F	P
Parts	9	0.761950	0.0846611	78193.2	0.000
Operators	2	0.000148	0.0000741	68.5	0.000
Operators * Parts	18	0.000019	0.0000011	0.7	0.786
Repeatability	60	0.000091	0.0000015		
Total	89	0.762209			

As shown in the table 7, the p-value for the Operator*Part was < 0.25, MINITAB ran the full model to define the Gage R&R statistics which means that it fitted the model with the interaction.

As shown in the table 8, the p-value for the Operator*Part was > 0.25, MINITAB passed over this from the full model which means that it fitted the model without the interaction.

Table 9 shows the Percentage of Contribution of glass for 24 inches using ANOVA method to calculate. If the percentage of contribution from Part-To-Part is larger than the total Gage R&R, most of the variations are due to differences between parts. On the other hand, if the percentage of contribution from Part-To-Part is less than the total Gage R&R, most of the variations arise from the measurement system (MINITAB User's Guide, 2000).

Table 9

Percentage of Contribution using ANOVA method for 24 inches

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000059	0.07
Repeatability	0.0000014	0.02
Reproducibility	0.0000044	0.05
Operator	0.0000039	0.04
Operators * Parts	0.0000005	0.01
Part-To-Part	0.0088359	99.93
Total Variation	0.0088418	100.00

Table 10 shows the Percentage of Contribution of glass for 48 inches.

Table 10

Percentage of Contribution using ANOVA method for 48 inches

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000038	0.04
Repeatability	0.0000014	0.02
Reproducibility	0.0000024	0.03
Operator	0.0000024	0.03
Part-To-Part	0.0094066	99.96
Total Variation	0.0094105	100.00

As shown in the above tables, since both of the percentages of contributions from Part-To-Part were larger than the total Gage R&R, most of the variations were due to differences between parts.

Table 11 shows the Number of Distinct Categories in measurement systems of glass for 24 and 48 inches using ANOVA method to calculate. According to the AIAG, an adequate measuring system needs at least five distinct categories (Measurement Systems Analysis Reference Manual, 1995).

Table 11

Number of Distinct Categories using ANOVA method for 24 and 48 inches

Source	24 inches	48 inches
Number of Distinct Categories	54	69

As shown in the above tables, both of measurement systems had Number of Distinct Categories greater than five so they were adequate measuring systems.

In the Components of Variation graph, if the percentage of contribution from Part-To-Part is larger than the Total Gage R&R, most of the variations are due to differences between parts. On the other hand, if the percentage of contribution from Part-To-Part is less than the total Gage R&R, most of the variations are due to the measurement system primarily repeatability (MINITAB User's Guide, 2000).

In the R Chart by Operator, if the graph is nearly level line, there is little difference between parts (MINITAB User's Guide, 2000).

In the Xbar Chart by Operator, if most of the points in the Xbar and R chart are outside the control limits, variations are mainly due to differences between parts. On the other hand, if most of the points in the Xbar and R chart are inside the control limits, the observed variations are mainly due to the measurement system (MINITAB User's Guide, 2000).

In the StdOrder by Parts graph, if the graph is non-level line, there are large differences between parts. If the graph is nearly level line, there is little difference between parts (MINITAB User's Guide, 2000).

In the StdOrder by Operators graph, if the graph is shown nearly by the level line, there are small differences between operators compared to the differences between parts (MINITAB User's Guide, 2000).

Table 12

Graph Analysis using ANOVA method for both 24 and 48 inches

Source	24 inches	48 inches
Components of Variation	most of the variation was due to differences between parts	most of the variation was due to differences between parts
R Chart by Operators	there were many differences between parts	there were many differences between parts
Xbar Chart by Operators	variation was mainly due to differences between parts	variation was mainly due to differences between parts
StdOrder by Parts	there were large differences between parts	there were large differences between parts
StdOrder by Operators	there were small differences between operators	there were small differences between operators

Table 13 shows comparison among the percentages of Repeatability, Reproducibility, and the Total Gage R&R for 24 and 48 inches.

Table 13

Comparison among the percentages of Repeatability, Reproducibility, and the Total Gage R&R

Size	Reproducibility	Repeatability	Total Gage R&R	Acceptable (<10%)
24 inches	0.05	0.02	0.07	Yes
48 inches	0.02	0.02	0.04	Yes

According to AIAG standard, the percentage of contribution of Gage R&R will be accepted if it is fewer than 10%. If it is between 10% and 30%, the measurement system may be acceptable depending on importance of application, cost of repairs or cost of gage, etc. If it is over than 30%, the measurement system is not satisfactory and it needed improvement (Measurement Systems Analysis Reference Manual, 1995). In conclusion, both of the measurement systems had the percentage of contribution of Gage R&R fewer than 10% so they could be decided that the measurement systems were acceptable and reliable. Most of the variations came from parts, not from instruments, operators, nor methods.

Chapter V: Discussion

Company XYZ is a high quality float glass manufacturer in Wisconsin. This company has flexible capabilities to produce a variety of thicknesses and dimension in glass. Two years ago, the company received complaints from customers regarding the quality of the glass and that it did not meet their expectations. The pieces of glass were either too small or too big that the customers received. The quality manager called all related people to solve this problem. Six months later, the quality manager added a digital measurement table into the production line. Unfortunately the measurement table could not solve this problem. After adding the table, there were still complaints from one new customer about the wrong size shipping. The initial analysis by the quality manager stated that the new customer did not have the same measurement method like the other customers because the other customers did not complain about the problem anymore. However, the new customer still mentioned that the problem was XYZ's and wanted them to solve it.

The purposes of this study were to determine if the measurement system could produce precise and accurate data, and if the precision and accuracy could solve the complaint problems by proving the measurement data to the customer. In addition, this study could evaluate the reliability of the measurement system that the manufacturing plant had recently applied in their production process.

For this Gage R&R study, the population was all sample parts in two different sizes, 24 inches and 48 inches, which had the same characteristics. The population also included three skillful operators who operated at the inspection process. All inspections were measured under the same condition, instrument, and setup. As part of the inspection process, there was a digital measurement table used to measure the dimension of the various pieces of glass. This measurement table measured the width dimension with high precision and accuracy. In addition, it also electronically recorded measurement data at the same time. When an operator measured a piece of glass, the measurement data was gathered by a computer into a data collection sheet file. The data collection sheet was designed by the researcher to easy compile the measurement data. Then, the data was entered in a software program, MINITAB version 15, and analyzed using ANOVA. The MINITAB software measured percentage of contribution on the variance components as repeatability, reproducibility, and part-to-part.

Limitations

The limitations of this study were:

1. This study was limited by work experience and available time of the researcher.
2. This study was limited by amount of sample parts.
3. This study did not control external environment which may affect the measurement system.
4. This study did not consider financial impacts for the Company XYZ.

Conclusion

This study evaluated 90 measurement data by using ANOVA method in the MINITAB software. From the results, the percentage of contribution of Gage R&R would be accepted because it was fewer than 10% according to AIAG standard. Most of the variation came from parts, not from instruments, operators, nor methods. The measurement systems could be acceptable and reliable. With this study, the Company XYZ knew that its measurement system was giving accurate and precise information.

If the measurement systems are not satisfactory, operators can know what the cause of problem is. Kappele & Raffaldi (2006, June) indicated that Gage R&R study provided guidance on how to improve a measurement system to make it reliable. This information helped operators to determine which function should be fixed to improve the measurement system. For instance, a high repeatability relative to reproducibility indicated the need for a better instrument. A high reproducibility relative to repeatability indicated the need for better operator training in the instrument and measurement method.

Recommendations

One of the recommendations for future research is to ensure that the operators follow the work instruction because there were some differences in the working steps while gathering the measurement data. Also, the sample parts should be picked randomly and not be chosen only because they are defective because it causes variation in part-to-part. The digital measurement table should be improved to operate easily and prevent mistakes from an operator. The inspection system should be a closed system which means that external environment cannot affect the system. Moreover, the company should concentrate on the production system instead of the measurement system because most of the variations came from parts. To control the quality of parts, the company should improve the production system to produce their products meet their customers' needs.

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Appendix A: Collected Measurement Data

Dimension of glass for 24 inches

Appraiser	Trial	Part No.										
		1	2	3	4	5	6	7	8	9	10	Average
A	1	23.875	23.954	24.016	24.076	24.140	23.881	23.939	23.997	24.062	24.119	24.006
	2	23.877	23.959	24.015	24.076	24.142	23.882	23.937	23.996	24.062	24.121	24.007
	3	23.874	23.957	24.018	24.077	24.142	23.883	23.937	23.996	24.063	24.119	24.007
	Average	23.875	23.957	24.016	24.076	24.141	23.882	23.938	23.996	24.062	24.120	24.006
	Range	0.003	0.005	0.003	0.001	0.002	0.002	0.002	0.001	0.001	0.002	0.002
B	1	23.876	23.959	24.020	24.084	24.144	23.885	23.940	24.001	24.063	24.123	24.010
	2	23.875	23.957	24.020	24.081	24.146	23.884	23.940	24.001	24.064	24.123	24.009
	3	23.875	23.957	24.019	24.080	24.144	23.883	23.940	23.999	24.062	24.121	24.008
	Average	23.875	23.958	24.020	24.082	24.145	23.884	23.940	24.000	24.063	24.122	24.009
	Range	0.001	0.002	0.001	0.004	0.002	0.002	0.000	0.002	0.002	0.002	0.002
C	1	23.874	23.955	24.017	24.074	24.139	23.880	23.937	23.994	24.058	24.117	24.005
	2	23.873	23.955	24.017	24.074	24.138	23.878	23.937	23.995	24.062	24.118	24.005
	3	23.873	23.955	24.017	24.077	24.139	23.881	23.937	23.997	24.060	24.119	24.006
	Average	23.873	23.955	24.017	24.075	24.139	23.880	23.937	23.995	24.060	24.118	24.005
	Range	0.001	0.000	0.000	0.003	0.001	0.003	0.000	0.003	0.004	0.002	0.002

Dimension of glass for 48 inches

Appraiser	Trial	Part No.										
		1	2	3	4	5	6	7	8	9	10	Average
A	1	47.862	47.928	47.992	47.938	48.132	47.890	47.950	48.014	47.889	48.138	47.973
	2	47.862	47.927	47.992	47.938	48.129	47.887	47.948	48.013	47.889	48.136	47.972
	3	47.859	47.926	47.991	47.937	48.133	47.886	47.948	48.013	47.888	48.136	47.972
	Average	47.861	47.927	47.992	47.938	48.131	47.888	47.949	48.013	47.889	48.137	47.973
	Range	0.003	0.002	0.001	0.001	0.004	0.004	0.002	0.001	0.001	0.002	0.002
B	1	47.865	47.930	47.994	47.939	48.135	47.888	47.950	48.016	47.890	48.137	47.974
	2	47.862	47.927	47.991	47.937	48.134	47.888	47.950	48.014	47.888	48.136	47.973
	3	47.863	47.928	47.991	47.937	48.131	47.887	47.949	48.014	47.888	48.136	47.972
	Average	47.863	47.928	47.992	47.938	48.133	47.888	47.950	48.015	47.889	48.136	47.973
	Range	0.003	0.003	0.003	0.002	0.004	0.001	0.001	0.002	0.002	0.001	0.002
C	1	47.859	47.925	47.989	47.935	48.129	47.885	47.945	48.011	47.888	48.132	47.970
	2	47.860	47.925	47.989	47.934	48.129	47.885	47.946	48.011	47.886	48.134	47.970
	3	47.859	47.925	47.992	47.934	48.132	47.887	47.946	48.010	47.887	48.135	47.971
	Average	47.859	47.925	47.990	47.934	48.130	47.886	47.946	48.011	47.887	48.134	47.970
	Range	0.001	0.000	0.003	0.001	0.003	0.002	0.001	0.001	0.002	0.003	0.002

Appendix B: Measurement System Analysis using MINITAB

Measurement Data analysis for 24 inches

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Parts	9	0.715736	0.0795262	26303.1	0.000
Operators	2	0.000241	0.0001203	39.8	0.000
Parts * Operators	18	0.000054	0.0000030	2.1	0.015
Repeatability	60	0.000085	0.0000014		
Total	89	0.716116			

Alpha to remove interaction term = 0.25

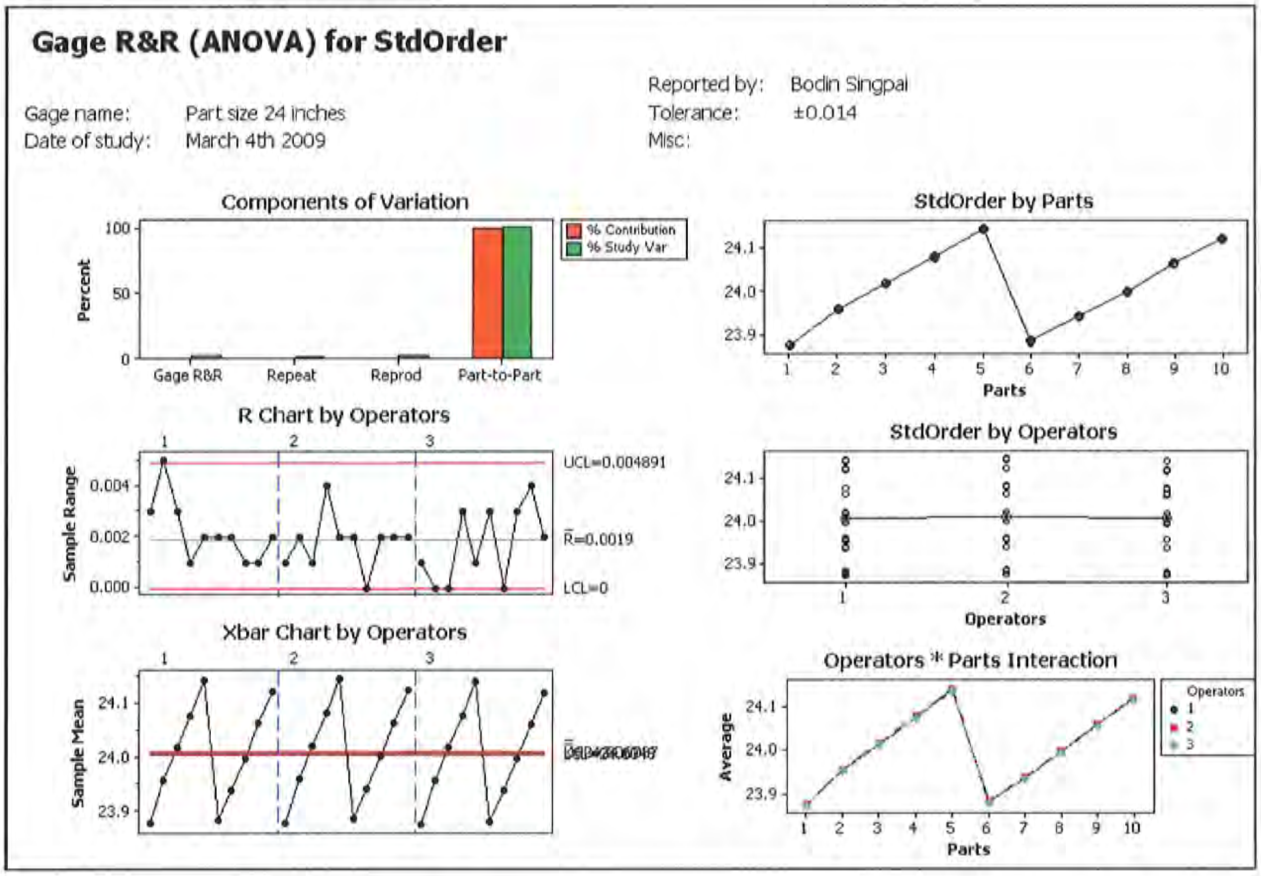
Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000059	0.07
Repeatability	0.0000014	0.02
Reproducibility	0.0000044	0.05
Operators	0.0000039	0.04
Operators*Parts	0.0000005	0.01
Part-To-Part	0.0088359	99.93
Total Variation	0.0088418	100.00

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gage R&R	0.0024221	0.014533	2.58
Repeatability	0.0011926	0.007155	1.27
Reproducibility	0.0021082	0.012649	2.24
Operators	0.0019775	0.011865	2.10
Operators*Parts	0.0007306	0.004383	0.78
Part-To-Part	0.0939995	0.563997	99.97
Total Variation	0.0940307	0.564184	100.00

Number of Distinct Categories = 54

Graph Analysis for 24 inches



Measurement Data analysis for 48 inches

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Parts	9	0.761950	0.0846611	78193.2	0.000
Operators	2	0.000148	0.0000741	68.5	0.000
Parts * Operators	18	0.000019	0.0000011	0.7	0.786
Repeatability	60	0.000091	0.0000015		
Total	89	0.762209			

Alpha to remove interaction term = 0.25

Two-Way ANOVA Table Without Interaction

Source	DF	SS	MS	F	P
Parts	9	0.761950	0.0846611	59587.0	0.000
Operators	2	0.000148	0.0000741	52.2	0.000
Repeatability	78	0.000111	0.0000014		
Total	89	0.762209			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000038	0.04
Repeatability	0.0000014	0.02
Reproducibility	0.0000024	0.03
Operators	0.0000024	0.03
Part-To-Part	0.0094066	99.96
Total Variation	0.0094105	100.00

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gage R&R	0.0019608	0.011765	2.02
Repeatability	0.0011920	0.007152	1.23
Reproducibility	0.0015570	0.009342	1.60
Operators	0.0015570	0.009342	1.60
Part-To-Part	0.0969878	0.581927	99.98
Total Variation	0.0970076	0.582046	100.00

Number of Distinct Categories = 69

Graph Analysis for 48 inches