Notes:

Measurement System Analysis Using Continuous Data

Key Learning Points

1. Describe how to set up measurement system analyses.
2. Explain how to generate diagnostic statistics
3. Explain how to evaluate the output and the measurement system.

Continuous Measurement System Study

- To quantify the amount of observed process variation due to error in the measurement system
- To evaluate new measurement devices before releasing them to operations
- To compare different types of measurement devices
- To evaluate a gage suspected of being deficient
- To evaluate impact of repairs
- To assure measurement error will not lead to a false product acceptance and/or SPC results

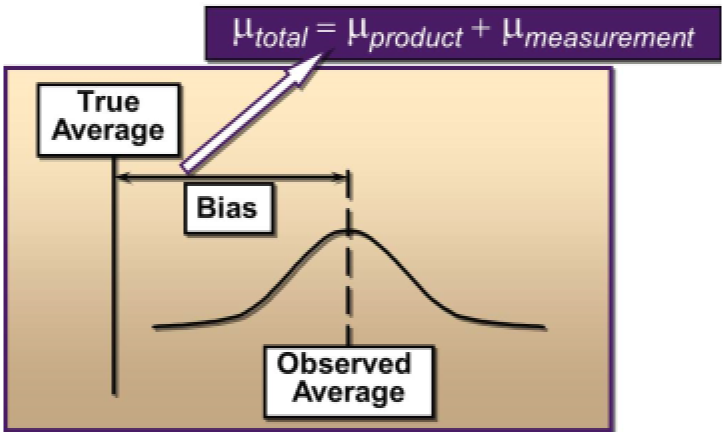
Measurement Variance

Measurement variance comes from:

Gage Bias

Gage Bias is the difference between the observed average of measurements and the true average. Establishing the true average is best determined by measuring with the most accurate measuring equipment available.

Eliminating Gage Bias is assured by a good calibration program!



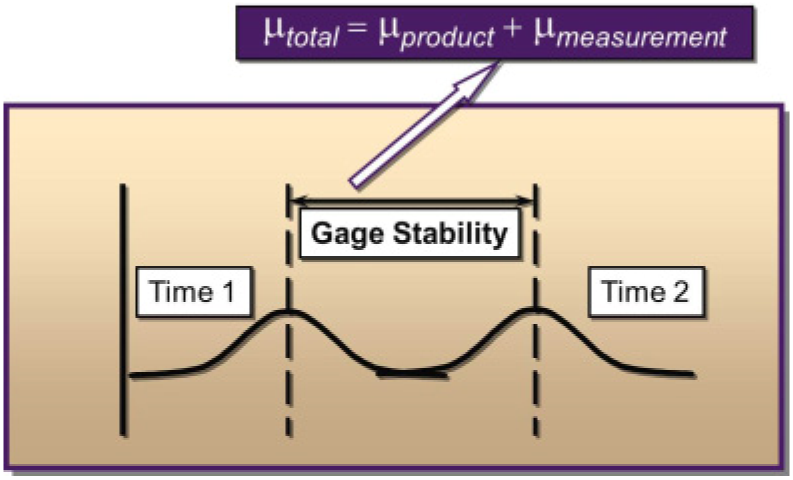
Excessive Bias May Be Caused By:

- Error in the reference or master
- Worn components
- Instrument made to wrong dimension
- Instrument measuring wrong characteristic
- Instrument not calibrated properly
- Instrument used improperly by appraiser

Notes:

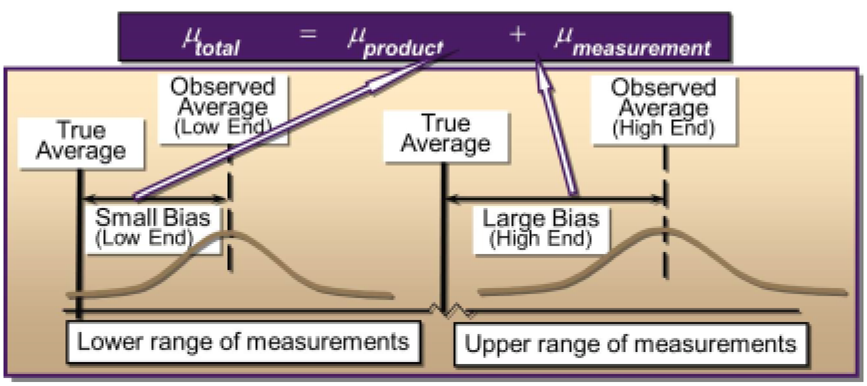
Gage Stability

Gage Stability refers to the difference in the average of at least two sets of measurements obtained with the same Gage on the same parts taken at different times.



Gage Linearity

Gage Linearity is the difference in the accuracy values through the expected operating range. It is a function of Gage selection. Linearity through the range of the spec should be part of the Gage qualification.



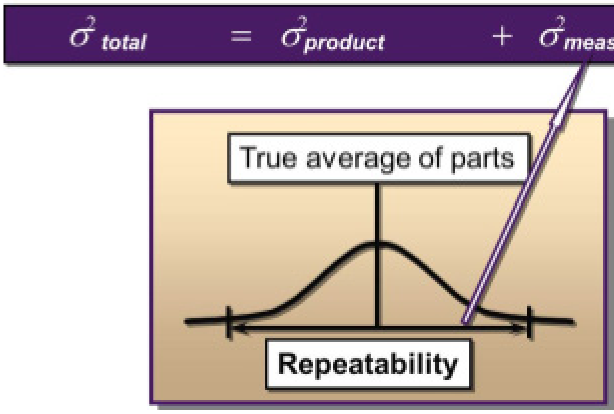
Linearity is the study of bias conditions throughout the measurement instrument range. If a measurement system has non-linearity, the possible causes are:

- Calibration has not properly covered the range of potential measurements
- Error in the master(s) covering the potential range of measurements
- Instrument deterioration
- Internal instrument design characteristics

Notes:

Gage Repeatability

Gage Repeatability is the variation in measurements obtained when one operator uses the same gage for measuring the identical characteristics of the same parts.

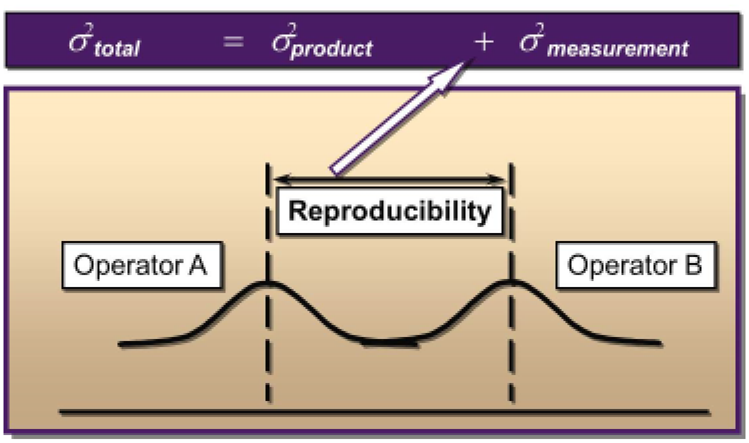


Repeatability of the measurement process determines if the measurement system's variability is consistent. Sources of repeatability error are:

- Inherent instrument variation because of design
- Instrument positional variation

Gage Reproducibility

Gage Reproducibility is the variation in the average of measurements made by different operators using the same gage when measuring identical characteristics of the same parts.



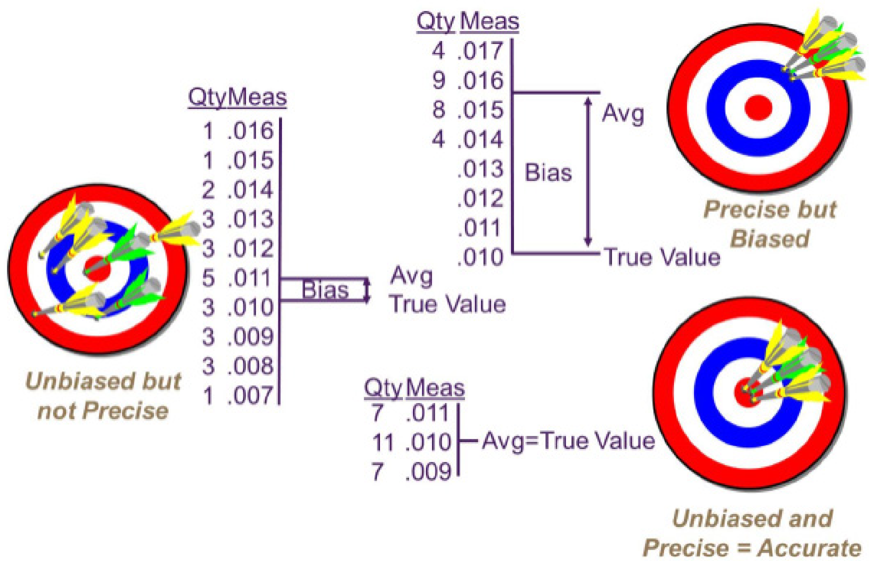
Reproducibility of the measurement process implies variability among appraisers is consistent. Sources of reproducibility errors are:

- Appraiser methods and techniques
- Training
- Procedures/methods

Notes:

- Shifts

Bias and Precision



Precision to Tolerance (P/T)

To qualify a Gage as capable of measuring to a product specification:

$$P/T = \frac{\text{Precision of Gage}}{\text{Tolerance Width}}$$

$$P/T = \frac{6 * \sqrt{\sigma_{MS}^2}}{USL - LSL} = \frac{6 * \sigma_{MS}}{USL - LSL}$$

Precision to Total Variation (P/TV)

To quantify the variation of a Gage compared to the total variation of the measurements to be studied:

$$P/TV = \frac{\text{Precision of Gage}}{\text{Total Process Variation}}$$

$$P/TV = \frac{6 * \sqrt{\sigma_{MS}^2}}{6 * \sqrt{\sigma_{total}^2}} = \frac{\sigma_{MS}}{\sigma_{total}}$$

Notes:

Acceptance Criteria

Notes:

There are three common methods used to qualify a measurement system:

- % Contribution
- % Study Variation
- Distinct Categories

The rules for each method are shown below:

	% Contribution	% Study Variation	Distinct Categories
Accept	< 1%	< 10%	> 10
Consider Critically	1% - 9%	10% - 30%	4 - 9
Reject	> 9%	> 30%	< 4

How to Complete a Measurement System Study for Continuous Data

1. Plan the agenda.
2. Determine the number of appraisers, samples, and repeat readings.
3. Choose appraisers who normally operate the instrument.
4. Use samples from the process representing its entire operating range.
5. Assure instrument discrimination is at least 1/10 of the expected process variation.
6. Assure the measurement study is following the normal measurement procedures.

Gage R&R Guidelines for MSA Studies

- Use at least two, but preferably three or more operators.
- Use at least 10 units that represent 80% of the observed process variation.
- Each operator should measure each unit at least 2 times.
- All standard measuring equipment should be evaluated.
- There should be a Gage R&R strategy for qualifying new operators and new equipment.

Completing a Continuous MSA Study

This example compares an item or part to a master specification. There are three appraisers which measure the thickness of ten widgets in two trials. The widgets are measured in inches.

Conducting Gage R&R Analysis In Minitab

1. Select samples representing at least 80% of the total process range.
2. Calibrate the Gage, or assure that it has been calibrated.
3. Set up the MINITAB® Worksheet for the Gage R&R study.
4. Have the first operator measure all the samples once in random order (Blind sampling, in which the operator does not know the identity of the part, should be used to reduce human bias. Parts must represent 80% of all long-term variability.)
5. Have the second operator measure all the samples once in random order; continue until all operators have measured the samples once (this is Trial 1).
6. Repeat steps 4-5 for the required number of trials.
7. Enter the data and tolerance information into MINITAB®.
8. Analyze the results by assessing the quality of the measurement system based on the guidelines, and determine follow-up actions.

Gage R&R Session Commands in Minitab

To set up the MINITAB® Worksheet for the Gage R&R study:

MINITAB®: Stat > Quality Tools > Gage Study > Create R&R Study Worksheets

- Enter numbers and names for operators and parts.
- Select a number and replicates for each part (this will create a randomized order for study).
- Add a column for observed value.

Enter the data and tolerance information into MINITAB®:

MINITAB®: Stat > Quality Tools > Gage Study > Gage R&R Study

- (Crossed)

MINITAB®: Stat > Quality Tools > Gage Study > Gage Run Chart

Step 1: Select Items or Parts From the Process

A project team selected 10 widgets outputted from their process. They made sure to represent at least 80% of the total process range.

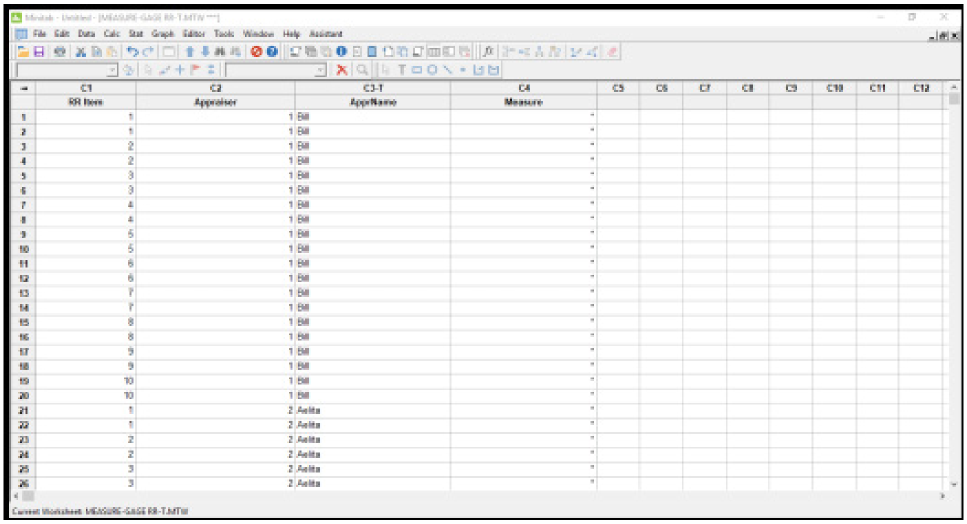
Notes:

Step 2: Calibrate the Gage (or Ensure that it has been Calibrated)

Before having anyone measure the widgets, the team had their measurement sensor (a digital dial caliper) calibrated to a known standard by a well-known local metrology company.

Step 3: Set up the Minitab Worksheet

Next the team selected their appraisers and set up their Minitab worksheet to be used to collect their data.



	C1 RR Item	C2 Appraiser	C3-T AppName	C4 Measure
1	1	1	Bill	*
2	1	1	Bill	*
3	2	1	Bill	*
4	2	1	Bill	*
5	3	1	Bill	*
6	3	1	Bill	*
7	4	1	Bill	*
8	4	1	Bill	*
9	5	1	Bill	*
10	5	1	Bill	*
11	6	1	Bill	*
12	6	1	Bill	*
13	7	1	Bill	*
14	7	1	Bill	*
15	8	1	Bill	*
16	8	1	Bill	*
17	9	1	Bill	*
18	9	1	Bill	*
19	10	1	Bill	*
20	10	1	Bill	*
21	1	2	Aelita	*
22	1	2	Aelita	*
23	2	2	Aelita	*
24	2	2	Aelita	*
25	3	2	Aelita	*
26	3	2	Aelita	*

Step 4: Appraisers Measure Items

At this point the appraisers, Bill, Aelita, and Jose, each measured the 10 widgets in random order. They completed this task twice, and the results were recorded in the Minitab spreadsheet.

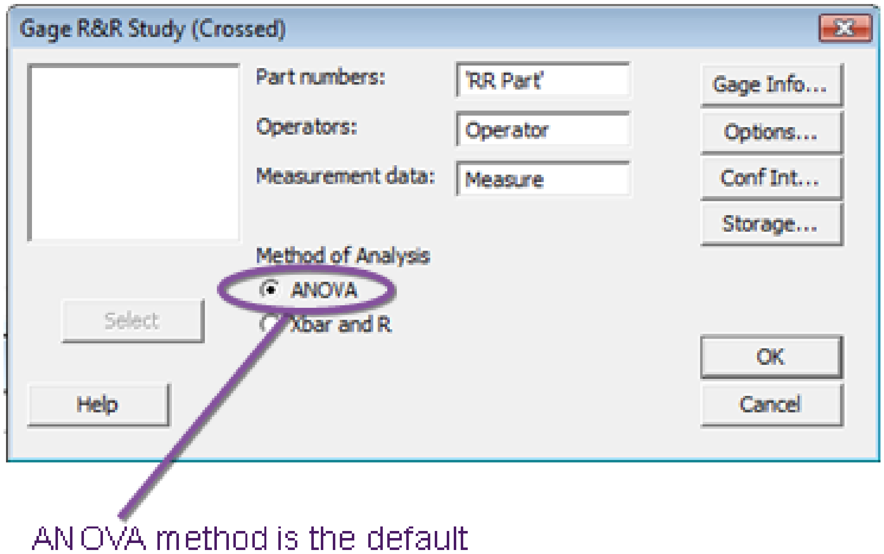
Step 5: Evaluate Measurement System

With collected data, the team was now ready to analyze their measurement system using the Analysis of Variance or ANOVA method in Minitab.

Analysis of Variance (ANOVA or AOV) is used to partition the total variance into its component parts. In this case, the team is able to assign variation to parts, which you expect to have, operators (which represents the human side of error), and repeatability (which represents the equipment side of error). An added benefit of the ANOVA method is the ability to look at the interaction between operator and part, that is, the condition in which operators have different performances depending on the part.

Notes:

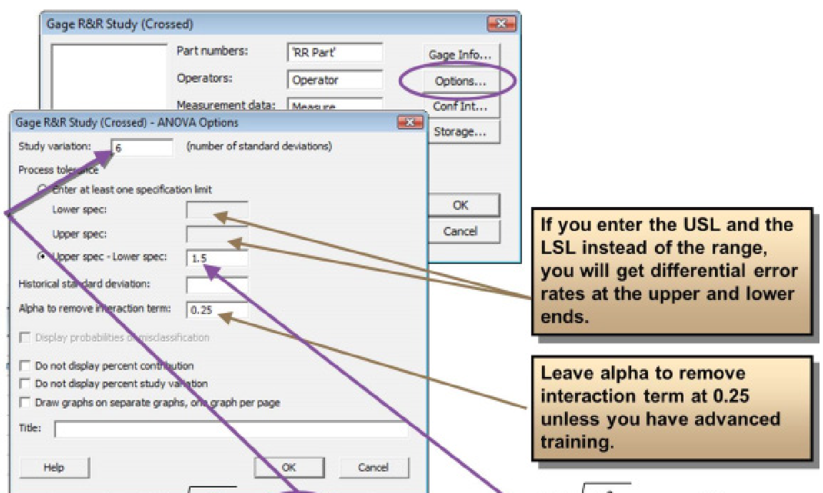
Minitab: Stat > Quality Tools > Gage Study > Gage R&R (Crossed)



Notes:

Minitab Analysis

Note that the denominator of the P/TV calculation cane be estimated from the samples used in the study or from a historical estimate.

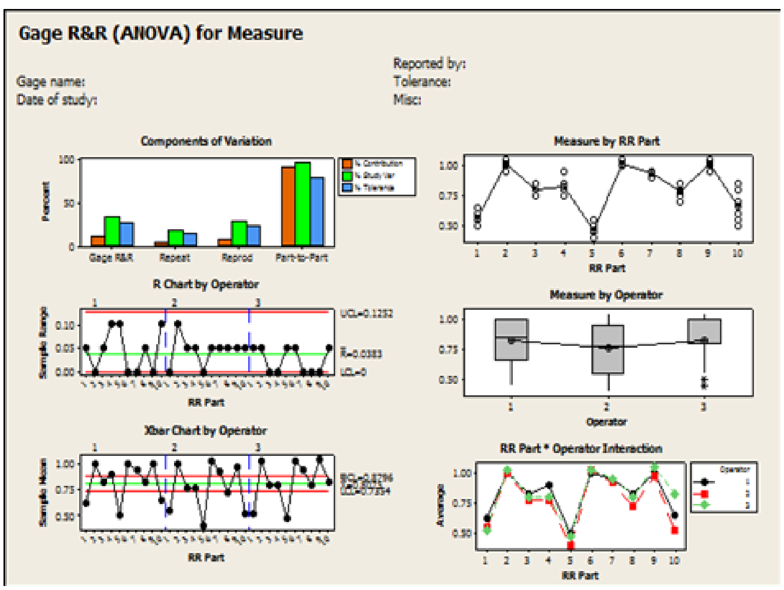


$$P/TV = \frac{6*\sqrt{\sigma^2_{MS}}}{6*\sqrt{\sigma^2_{total}}} = \frac{6*\sigma_{MS}}{6*\sigma_{total}} \qquad P/T = \frac{6*\sqrt{\sigma^2_{MS}}}{USL-LSL} = \frac{6*\sigma_{MS}}{USL-LSL}$$

ANOVA Session Window Output

```
Gage R&R Study - ANOVA Method

Two-Way ANOVA Table With Interaction

Source               DF       SS        MS        F      P
RR Part               9  2.05871  0.228745  39.7178  0.000
Operator              2  0.04800  0.024000   4.1672  0.033
RR Part * Operator   18  0.10367  0.005759   4.4588  0.000
Repeatability        30  0.03875  0.001292
Total                59  2.24912


Alpha to remove interaction term = 0.25


Gage R&R

                                 %Contribution
Source               VarComp      (of VarComp)
Total Gage R&R     0.0044375             10.67
  Repeatability    0.0012917              3.10
  Reproducibility  0.0031458              7.56
    Operator       0.0009120              2.19
    Operator*RR Part 0.0022338            5.37
Part-To-Part       0.0371643             89.33
Total Variation    0.0416018            100.00


Process tolerance = 1.5


                                  Study Var  %Study Var  %Tolerance
Source               StdDev (SD)   (6 * SD)       (%SV)  (SV/Toler)
Total Gage R&R          0.066615    0.39969       32.66       26.65
  Repeatability         0.035940    0.21564       17.62       14.38
  Reproducibility       0.056088    0.33653       27.50       22.44
    Operator            0.030200    0.18120       14.81       12.08
    Operator*RR Part    0.047263    0.28358       23.17       18.91
Part-To-Part            0.192781    1.15668       94.52       77.11
Total Variation         0.203965    1.22379      100.00       81.59


Number of Distinct Categories = 4
```

ANOVA Graphical Output



Notes:

Gage R&R Study - ANOVA Method

Two-Way ANOVA Table with Interaction

Source	DF	SS	MS	F	P
RR Part	9	2.05871	0.228745	39.7178	0.000
Operator	2	0.04800	0.024000	4.1672	0.033
RR Part * Operator	18	0.10367	0.005759	4.4588	0.000
Repeatability	30	0.03875	0.001292		
Total	59	2.24912			

$$s^2 = \frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}$$

Gage R&R Variation Compnents

If your measurement system is good, where will you find most of your variation?

Variance because of the measurement system (broken down into repeatability and reproducibility)

Gage R&R Study - ANOVA Method

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0044375	10.67
Repeatability	0.0012917	3.10
Reproducibility	0.0031458	7.56
Operator	0.0009120	2.19
Operator*RR Part	0.0022338	5.37
Part-To-Part	0.0371643	89.33
Total Variation	0.0416018	100.00

Variance due to the parts

Total variance

Gage R&R Results

Variance because of the measurement system (broken down into repeatability and reproducibility)

Gage R&R Study - ANOVA Method

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0044375	10.67
Repeatability	0.0012917	3.10
Reproducibility	0.0031458	7.56
Operator	0.0009120	2.19
Operator*RR Part	0.0022338	5.37
Part-To-Part	0.0371643	89.33
Total Variation	0.0416018	100.00

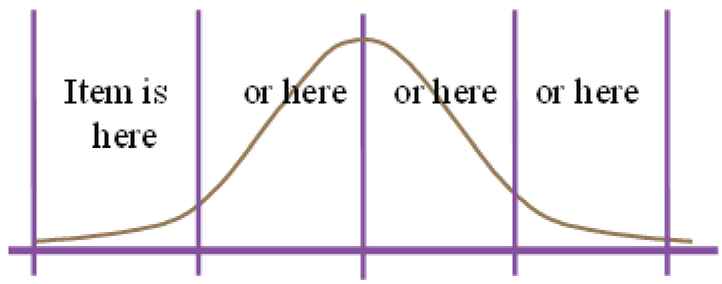
Variance due to the parts

Total variance

Notes:

Gage R&R Distinct Categories

In this example there are 4 distinct categories. This means that this measurement system can distinguish 4 distinct categories. Distinct categories are the groups within your process that your measurement system can discern.



Distinct Categories Rules

The more distinct categories that a measurement system has, the better it is.

How a Team Should Act	Distinct Categories
No issues with the measurement system. It can be used with not problems	> 10
The measurement system can be used, but the team should look closely at it. Keep a close eye on criticality and cost	4 - 9
Reject the measurement system.	< 4

Calculating Distinct Categories

Source	VarComp
Total Gage R&R	0.0044375
Repeatability	0.0012917
Reproducibility	0.0031458
Operator	0.0009120
Operator*RR Part	0.0022338
Part-To-Part	0.0371643
Total Variation	0.0416018

$$\text{Categories} = \text{Round}\left\{\sqrt{2\,\frac{\sigma^2_{Parts}}{\sigma^2_{MS}}}\right\} = \text{Round}\left\{\sqrt{2\,\frac{0.037164}{0.004438}}\right\}$$

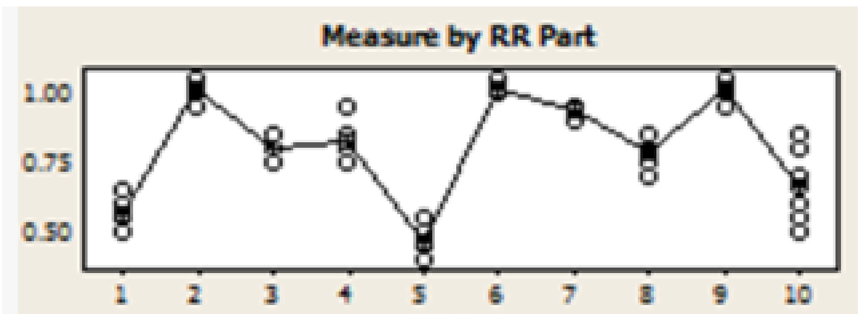
$$= \text{Round}\,\{4.33\}$$

Notes:

Gage R&R Graphical Output

Measure by RR Part:

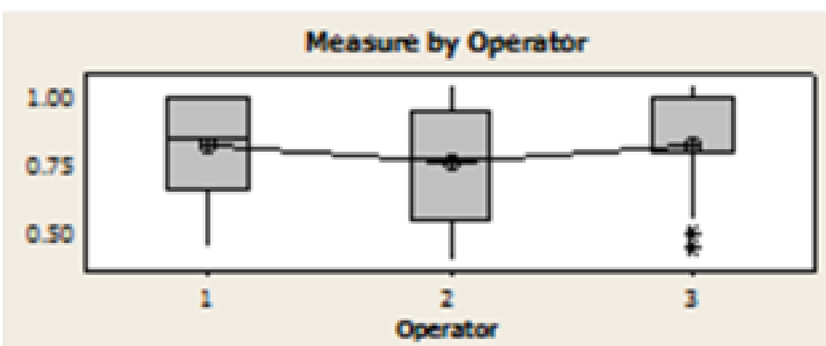
- Shows the ability of all of your operators to obtain the same readings for each part.
- Also shows the ability of your measurement system to distinguish between parts (amount of overlap).
- What would the ideal graph look like?



Measure By Operator:

Shows if any operator(s) had higher or lower readings (on average) than the others.

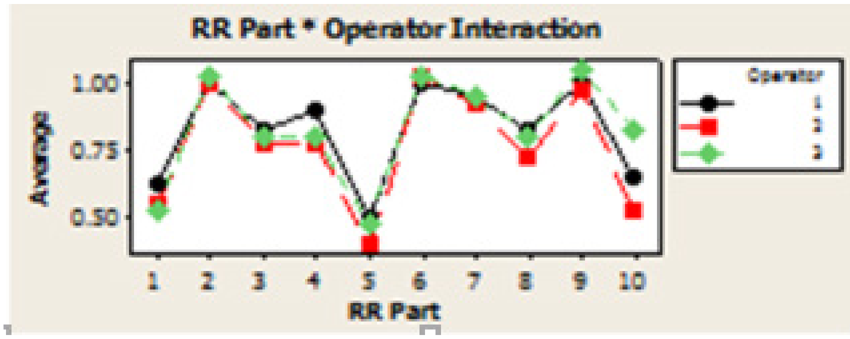
What would the ideal graph look like?



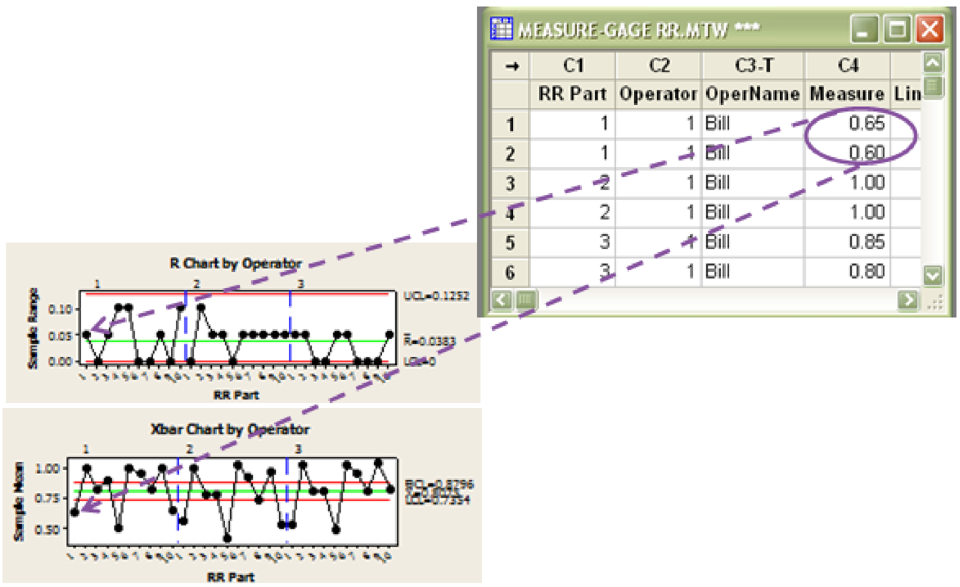
Notes:

Operator * RR Part Interaction

- Shows if any given part(s) was hard to manage for any given operator(s).
- Appears as though at least two of the operators had trouble measuring part #10.
- What would the ideal graph look like?



Gage R&R Xbar & R



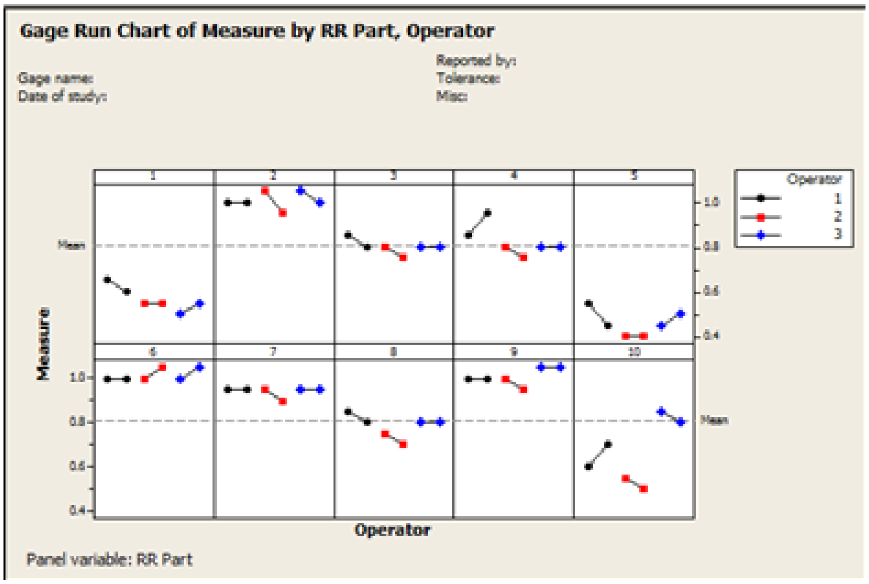
→	C1	C2	C3-T	C4
	RR Part	Operator	OperName	Measure
1	1	1	Bill	0.65
2	1	1	Bill	0.60
3	2	1	Bill	1.00
4	2	1	Bill	1.00
5	3	1	Bill	0.85
6	3	1	Bill	0.80

Notes:

Minitab Gage Run Chart

Gage Run Charts show measurements by operator and part ID. They allow you to visualize repeatability and reproducibility within and between an operator and a part. When looking at the chart, the center line is the overall average of the parts.

Minitab: Stat > Quality Tools > Gage Study > Gage Run Chart



Practical Conclusions

This gage had % Contribution and % Study Variation values outside the acceptance criteria. The number of distinct categories was just barely better than the rejection level.

In particular, repeatability and the measures for Part #10 seemed problematic.

Further investigation is needed, to be followed by corrective action and training, then a retest.

- % Contribution = 10.67
- % Study Variation = 32.66
- # of Distinct Categories = 4

Troubleshooting Poor Gage Capability

- If a dominant source of variation is repeatability (equipment), you need to replace, repair, or otherwise adjust the equipment.
- If, in consultation with the equipment vendor or upon searches of industry literature, you find that the gage technology that you are using is "state-of-the-art" and it is performing to its specifications, you will have to learn to live with it. One solution to this problem is to use signal averaging.
- If a dominant source of variation is reproducibility (operator), you must

Notes:

address either training or the quality and use of your standard process or measurement procedures. You should look for differences between operators to give you some indication as to whether it is a training, skill, and/or procedure problem.

- Evaluate the specifications. Are they reasonable?
- If the gage capability is marginal (as high as 30% of tolerance) and the process is operating at a high capability (Cpk greater than 2), then the Gage is probably not hindering you and you can continue to use it.

Controlling Repeatability – Short Term Solution

This technique should be used as a short-term approach to perform a study. For the long-term you should fix the gage.

This technique takes advantage of the Central Limit Theorem. Recall the earlier discussion that the variance of the distribution of averages is less than the variance of a distribution of individuals.

If you want to decrease gage error, take advantage of the standard error square root of the sample. The signal averaging technique uses: $1/\sqrt{n}$

n=the number of repeat measures taken on the same part of the measurement. This is the average of "n" readings. An example of this is: A gage error of 50 % can be cut in half if your point estimate is an average of 4 repeat measurements.
$1/\sqrt{4} = 1/2 = 0.5$

Gage R&R Study: Analysis Methods

Xbar-R Method

- This is a useful approach for estimating variation and percent of process variation, as well as tolerance for total measurement system.
- This includes variation components: Repeatability, Reproducibility, and can separate operator and part, but not operator-part interactions (weakness).
- Outliers will have great influence on Xbar - R Method.

ANOVA Method

- Analysis of Variance, or ANOVA is the preferred method to analyze measurement systems.

  This method is more precise.
- It can separate operator-part interactions.
- It leverages the power of Variance Partitioning through Analysis of Variance.

Notes:

- It is facilitated by computers and requires basic statistical knowledge to properly interpret output.

When Should MSA Be Used?

MSA should be used whenever a gage is used to evaluate the quality of a good. Gage R&R is used when measuring continuous variables.

- Bias – the difference between the observed and true measurements
- Stability – ability to maintain calibration over time
- Linearity – accuracy throughout the expected range of measurements
- Repeatability – One operator matching their own readings
- Reproducibility – Operators matching each other

Pitfalls to Avoid

- All measurement systems verifying critical to quality characteristics should be validated.
- Do not assume calibration is sufficient.
- Do not assume an annual calibration cycle is automatically correct.
- Recognize operators differences.
- Do not accept marketing estimates of tester variation.
- Samples must reflect the production range.
- Only use trained operators using standard methods.

Notes:

