Welcome to the 10th Annual So Cal Quality Conference 2017

Presented by:

ASQ Section 0700
Los Angeles Section
The Global Voice of Quality™

ASQ Section 0701
Orange Empire Section
The Global Voice of Quality™

ASQ Section 0702
San Gabriel Valley Section
The Global Voice of Quality™

ASQ Section 0706
San Fernando Valley Section
The Global Voice of Quality™
Please support our gracious Sponsors:

Gold Level
Silver Level

Minitab

GreenSoft Technology, Inc.

UCI Division of Continuing Education

Premiere Resource
Bronze Level

Edwards

Johnson & Johnson
Family of Companies
Measurement Systems Analysis

VARIABLE GAGE R&R METRICS, APPLICATIONS AND ROOT CAUSE ANALYSIS

Created and presented by: Gabor Szabo
Measurement Systems Analysis – Introduction

In the world of quality, there has always been a need for reliable data in order to make data-based decisions.

• Inspections – accepting or rejecting parts based on inspection results
• Improvement activities and projects – process and other improvement efforts/projects
• Any measurement activity that has an impact on quality or the organization

Questions to ask:
• How do you ensure that you can rely on your data and it reflects reality?
• How does one define a measurement system?
Objectives

By the end of this presentation we will have covered

• Basics of Measurement Systems Analysis
• Overview of Variable Gage R&R Study Metrics
• Application of Metrics
• Root Cause Analysis, Tools
Measurement System Definition

**What – How – Who**

- **What:** Characteristic of interest
  Examples: length, diameter, tensile strength, angle, waiting time, weight, number of cracks/voids (on part surface)

- **How:** Measurement method – includes the gage and the measurement procedure/technique
  Examples: naked eye, steel ruler, caliper, CMM and automated measurement program, spectrometer, microscope

- **Who:** Inspectors/Operators
  Examples: receiving inspectors, engineers, technicians
Measurement System Analysis – Accuracy/Bias and Precision

Accuracy/Bias
- Bias: the difference between the average of observed measurements and a master value
  - Linearity: accuracy through the expected range of measurements
  - Stability: accuracy over time

LINEARITY/BIAS STUDIES

Precision: Measurement variation
- Repeatability: consistency of measurements
- Reproducibility: difference between operators

GAGE R&R STUDIES
Accuracy – Precision

Precise
Inaccurate

Mean of measurements  Master value

Accurate
Imprecise

Master value
Mean of measurements

Accurate
Precise

Mean of measurements

Master value
Mean of measurements

Inaccurate
Imprecise
Studies Addressing Precision – Gage R&R Studies

- **Planned** studies to estimate variation attributed to the measurement system. Gage R&R Studies *only* assess precision (repeatability and reproducibility).
  - Study plan: samples, operators, trials
    The multiply of the above study elements for a *number of opportunities (or study sample size)*. Example: 10 samples x 3 operators x 3 trials.
  - Types:
    - **Variable** – variable output (continuous numerical values)
    - **Attribute** – attribute output (pass/fail, good/bad etc.)
  - Non-Destructive
  - Destructive

- History: Developed by automotive industry in the 1960’s. Initially the Average-Range method was used; the ANOVA method was developed later on (uses sum of squares to estimate standard deviation, which is a more accurate estimation than what the Average-Range method provides)

Components of Variation in a Variable Gage R&R Study

Process mean ($\mu$)
Specification limits (LSL, USL)

**Tolerance** = USL - LSL

**Observed Part-To-Part Variation**
also called Total Variation

**True Part-To-Part Variation**

**Measurement System Variation (Total GR&R)**

Reproducibility
Repeatability

Minitab
%Tolerance metric

<table>
<thead>
<tr>
<th>Source</th>
<th>VarComp (of VarComp)</th>
<th>%Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Gage R&amp;R</td>
<td>0.00000000</td>
<td>17.72</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>0.00000000</td>
<td>12.69</td>
</tr>
<tr>
<td>Operator</td>
<td>0.00000000</td>
<td>5.03</td>
</tr>
<tr>
<td>Operator*Sample</td>
<td>0.00000000</td>
<td>0.00</td>
</tr>
<tr>
<td>Part-To-Part</td>
<td>0.00000001</td>
<td>100.00</td>
</tr>
<tr>
<td>Total Variation</td>
<td>0.00000001</td>
<td>82.28</td>
</tr>
</tbody>
</table>

Measurement System Variation (Total GR&R) = Tolerance

Tolerance

Sigma Multiplier

GR&R [% Tolerance] = Measurement System Variation (Total GR&R) / Tolerance

Repeatability [% Tolerance] = Measurement System Variation (Total GR&R) / Repeatability

Reproducibility [% Tolerance] = Measurement System Variation (Total GR&R) / Reproducibility

Number of Distinct Categories = 3
%Tolerance metric – Repeatability and Reproducibility

- Because they are calculated and expressed in units of standard deviation – standards deviations are not additive; variances are.
- Since standard deviation is the square root of variance, the aggregate of Repeatability and Reproducibility is calculated based on the Pythagorean Theorem.

\[ A^2 + B^2 = C^2 \]

\[ \text{Total GR&R}^2 = \text{Repeatability}^2 + \text{Reproducibility}^2 \]

\[ \text{Total Variation (Part-To-Part + Total GR&R)}^2 = \text{Part-To-Part Variation}^2 + \text{Total GR&R}^2 \]

\[ \text{Total Variation (Part-To-Part + Total GR&R)} = \sqrt{\text{Part-To-Part Variation}^2 + \text{Total GR&R}^2} \]
%Tolerance metric - Application

- Application: inspections where the inspection result is compared to a specification and an accept/reject decision is made.

Examples: inspection activities (receiving inspection, in-process inspections, etc.), capability studies

- Sample selection: Since the Total Variation component is not part of the %Tolerance formula, sample selection does not have an affect on the %Tolerance result.

- Acceptance criteria guidelines for %Tolerance per AIAG MSA Reference Manual 4th edition:

<table>
<thead>
<tr>
<th>&lt; 10%</th>
<th>Acceptable measurement system.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 – 30%</td>
<td>May be acceptable for some applications. Decision should be based on feature criticality, cost of measurement device, etc.</td>
</tr>
<tr>
<td>&gt; 30%</td>
<td>Unacceptable measurement system. Every effort should be made to improve the measurement system.</td>
</tr>
</tbody>
</table>
%Tolerance metric - Application

- Effect on process capability index $C_p/P_p$
**%Study Variation metric**

<table>
<thead>
<tr>
<th>Source</th>
<th>VarComp</th>
<th>%Contribution (of VarComp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Gage R&amp;R</td>
<td>0.0000000</td>
<td>17.72</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.0000000</td>
<td>12.69</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>0.0000000</td>
<td>5.03</td>
</tr>
<tr>
<td>Operator</td>
<td>0.0000000</td>
<td>0.00</td>
</tr>
<tr>
<td>Operator*Sample</td>
<td>0.0000000</td>
<td>5.03</td>
</tr>
<tr>
<td>Part-To-Part</td>
<td>0.0000001</td>
<td>82.25</td>
</tr>
<tr>
<td>Total Variation</td>
<td>0.0000000</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Process tolerance = 0.01

**Sigma Multiplier**

<table>
<thead>
<tr>
<th>Source</th>
<th>StdDev (SD)</th>
<th>Study Var (6 ~ SD)</th>
<th>%Study Var (ISV)</th>
<th>%Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Gage R&amp;R</td>
<td>0.0001357</td>
<td>0.00003145</td>
<td>49.09</td>
<td>8.14</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.0001149</td>
<td>0.00005592</td>
<td>31.62</td>
<td>6.85</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>0.0000723</td>
<td>0.00001310</td>
<td>22.43</td>
<td>4.34</td>
</tr>
<tr>
<td>Operator</td>
<td>0.0000000</td>
<td>0.00000000</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Operator*Sample</td>
<td>0.0000723</td>
<td>0.00004340</td>
<td>22.43</td>
<td>4.34</td>
</tr>
<tr>
<td>Part-To-Part</td>
<td>0.0002925</td>
<td>0.00017553</td>
<td>90.71</td>
<td>17.55</td>
</tr>
<tr>
<td>Total Variation</td>
<td>0.0003225</td>
<td>0.00019358</td>
<td>100.00</td>
<td>19.35</td>
</tr>
</tbody>
</table>

**Measurement System Variation (Total GR&R)**

\[
\text{Repeatability} = \text{Total Variation (Part-To-Part + Total GR&R)} \times \text{Repeatability Multiplier}
\]

\[
\text{Reproducibility} = \text{Total Variation (Part-To-Part + Total GR&R)} \times \text{Reproducibility Multiplier}
\]

\[
\text{GR&R [% Study Variation]} = \frac{\text{Measurement System Variation (Total GR&R)}}{\text{Total Variation (Part-To-Part + Total GR&R)}}
\]

\[
\text{Repeatability [% Study Variation]} = \frac{\text{Repeatability}}{\text{Total Variation (Part-To-Part + Total GR&R)}}
\]

\[
\text{Reproducibility [% Study Variation]} = \frac{\text{Reproducibility}}{\text{Total Variation (Part-To-Part + Total GR&R)}}
\]
%Study Variation metric – Application

• Application: activities where process changes, shifts or drifts need to be identified or monitored.

Examples: process/continuous improvement activities, such as SPC, Design of Experiments, etc.

• Sample selection: Since the Total Variation component is part of the %Study Variation formula, the %Study Variation metric is affected by sample selection.

\[
\text{GR&R [\% Study Variation]} = \frac{\text{Measurement System Variation (Total GR&R)}}{\text{Total Variation (Part-To-Part + Total GR&R)}}
\]

• Acceptance criteria guidelines for %Study Variation per AIAG MSA Reference Manual 4th edition:

<table>
<thead>
<tr>
<th></th>
<th>Acceptance criteria guidelines</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 10%</td>
<td>Acceptable measurement system. Measurement system able to distinguish parts or detect process shifts.</td>
</tr>
<tr>
<td>10 – 30%</td>
<td>May be acceptable for some applications. Decision should be based on feature criticality, cost of measurement device, etc.</td>
</tr>
<tr>
<td>&gt; 30%</td>
<td>Unacceptable measurement system. Every effort should be made to improve the measurement system.</td>
</tr>
</tbody>
</table>
%Study Variation vs. %Contribution metrics

%Study Variation – uses standard deviations, non-additive

<table>
<thead>
<tr>
<th>Source</th>
<th>StdDev (SD)</th>
<th>(6 x SD)</th>
<th>%Study Var</th>
<th>%Study Var / %Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Gage R&amp;R</td>
<td>0.00011357</td>
<td>0.00008145</td>
<td>42.03%</td>
<td>8.14%</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.0001149</td>
<td>0.0000892</td>
<td>35.62%</td>
<td>6.39%</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>0.00000023</td>
<td>0.00000140</td>
<td>22.43%</td>
<td>4.34%</td>
</tr>
<tr>
<td>Operator</td>
<td>0.00000060</td>
<td>0.00000040</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Operator*Sample</td>
<td>0.00000023</td>
<td>0.00000140</td>
<td>22.43%</td>
<td>4.34%</td>
</tr>
<tr>
<td>Part-To-Part</td>
<td>0.00002935</td>
<td>0.00001755</td>
<td>90.71%</td>
<td>17.55%</td>
</tr>
<tr>
<td>Total Variation</td>
<td>0.0003225</td>
<td>0.00019350</td>
<td>100.00%</td>
<td>19.35%</td>
</tr>
</tbody>
</table>

%Contribution – uses variances, additive

Acceptance criteria guidelines for %Contribution per AIAG MSA Reference Manual 4th edition:

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1%</td>
<td>Acceptable measurement system. Measurement system able to distinguish parts or detect process shifts.</td>
</tr>
<tr>
<td>1 – 9%</td>
<td>May be acceptable for some applications. Decision should be based on feature criticality, cost of measurement device, etc.</td>
</tr>
<tr>
<td>&gt; 9%</td>
<td>Unacceptable measurement system. Every effort should be made to improve the measurement system.</td>
</tr>
</tbody>
</table>
Number of Distinct Categories

Number of Distinct Categories (also called Discrimination Ratio)*

- It represents the number of non-overlapping confidence intervals that will span the range of product variation, i.e. it defines the number of groups within your process data that your measurement system can distinguish. “Effective gage resolution”

- The higher the number, the better the measurement system at distinguishing parts from one another

Formula: \( ndc = \sqrt{\frac{\sigma_{\text{part}}}{\sigma_{\text{gage}}}} \) (rounded down to nearest whole number)

Acceptance criteria guidelines per AIAG MSA Reference Manual 4th edition:

- \( ndc = 1 \): One part cannot be distinguished from others.

- \( ndc = 2\text{-}4 \): The data can be split into 2-4 groups: e.g. high and low (2), low-middle-high (3)

- \( ndc \geq 5 \): Recommended. Measurement system capable of distinguishing parts from each other. Can be used for process control.

<table>
<thead>
<tr>
<th>Source</th>
<th>Study Var</th>
<th>%Study Var</th>
<th>%Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Gage R&amp;R</td>
<td>0.0001357</td>
<td>0.0008145</td>
<td>42.09</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.0001149</td>
<td>0.0006892</td>
<td>35.62</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>0.0000723</td>
<td>0.0004810</td>
<td>22.43</td>
</tr>
<tr>
<td>Operator</td>
<td>0.0000000</td>
<td>0.0000000</td>
<td>0.00</td>
</tr>
<tr>
<td>Operator*Sample</td>
<td>0.0000723</td>
<td>0.0004810</td>
<td>22.43</td>
</tr>
<tr>
<td>Part-To-Part</td>
<td>0.0002925</td>
<td>0.0017553</td>
<td>90.71</td>
</tr>
<tr>
<td>Total Variation</td>
<td>0.0005225</td>
<td>0.0019350</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Number of Distinct Categories vs. %Study Variation

- Number of Distinct Categories and %Study Variation metrics are inversely proportional: the higher the %Study Variation, the lower the Number of Distinct Categories.

The relationship between \( ndc \) and %Study Variation

<table>
<thead>
<tr>
<th>% Study Var</th>
<th>ndc</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>141.414 ~ 141</td>
</tr>
<tr>
<td>5</td>
<td>28.249 ~ 28</td>
</tr>
<tr>
<td>10</td>
<td>14.017 ~ 14</td>
</tr>
<tr>
<td>20</td>
<td>6.928 ~ 6</td>
</tr>
<tr>
<td>27</td>
<td>5.043 ~ 5</td>
</tr>
<tr>
<td>28</td>
<td>4.849 ~ 4</td>
</tr>
<tr>
<td>30</td>
<td>4.497 ~ 4</td>
</tr>
<tr>
<td>31</td>
<td>4.337 ~ 4</td>
</tr>
<tr>
<td>32</td>
<td>4.187 ~ 4</td>
</tr>
<tr>
<td>33</td>
<td>4.045 ~ 4</td>
</tr>
<tr>
<td>34</td>
<td>3.912 ~ 3</td>
</tr>
</tbody>
</table>

\( ndc \) formula: \( ndc = \sqrt{2 \frac{\sigma_{part}}{\sigma_{gage}}} \)

%Study Variation formula: \( \%SV = \frac{\sigma_{gage}}{\sigma_{total}} \times 100 \)

**TAKEAWAY:** %Study Variation, %Contribution and Number of Distinct Categories all mean the same thing, expressed in different ways!
What if a Gage R&R Study fails? – Root Cause Analysis

• Potential root causes need to be investigated to determine what is causing excess measurement system variation

• Corrective action needs to be taken based on the root causes identified

• Root causes can be related to:
  • Gage
  • Method/Procedure
  • Samples
  • Inspection Fixture
  • Environment
  • Operators/Inspectors

• Root causes can affect
  • Repeatability
  • Reproducibility
  • Both
Potential Root Causes of Measurement System Variation

Environment
- Ambient temp.
- Humidity
- Vibration
- Lighting conditions
- Fixture/Nest Design
- Glossy/Matte
- Adequate Datum(s)

Fixture

Method/Procedure
- Sample clamping
- Measurement location/points
- Procedure too vague / No procedure
- Fixture/Nest Build (Tolerances)
- Elastic deformation
- Glossy/Matte
- Adequate Datum(s)

Part

Gage
- Calibration
- Gage linearity
- Verification
- Gage stability
- PM
- Accuracy/Bias
- Cleanliness
- Understanding Procedure/Drawing
- Stress/Pressure
- Attitude
- Fatigue
- Skill
- Training
- Experience

Man

Measurement System Variation
What if a Gage R&R Study fails? – Root Cause Analysis

Example of Typical Root Causes:

• Measurement method/procedure not defined well enough so operators may interpret it subjectively
  • Measurement location not defined well enough
  • Sample positioning not defined well enough
  • Measurement parameters not defined well enough

• Too much inherent measurement system variation – measurement system cannot be used for measurement application

• Inadequate clamping of sample in inspection fixture

• Insufficient gage resolution or rounded/truncated measurement results (Rule of Ten)

• Difference in operator skills – experience and level of training received
What if a Gage R&R Study fails? – Root Cause Analysis Tools

Gage R&R Study graph

Graphical representation of Components of Variation (in relation to %Contribution, %Study Variation, %Tolerance)

Range chart: graphically displays operator consistency (Repeatability). Any points outside of the control limits show that the operator is not measuring.

Average chart: compares part-to-part variation to the Repeatability component. Ideally shows lack of control.

By Part: all study measurement arranged by sample. Sample averages connected by line. Ideally, multiple measurements for each part show little variation.

By Operator: helps assess measurement averages and variability are consistent across operators. Ideally, the line if parallel to the X axis.

Sample-Operator Interaction: Displays average measurements by each operator for each sample. Ideally, the lines are virtually identical.
What if a Gage R&R Study fails? – Root Cause Analysis Tools

Multi-Vari chart

Graphical representation of the relationships between a response (measurement result) and factors (trial, sample, operator).

It can help:
- Identify patterns of variation (operator-to-operator, trial-to-trial etc.)
- Identify outliers
- Identify which root causes the improvement efforts should be focused on eliminating

Panel variable: Operator

(this chart was run for Gage R&R Study from earlier)
What if a Gage R&R Study fails? – Root Cause Analysis Tools

Multi-Vari chart

Always assess statistical vs. practical significance, and keep the measurement application in mind.

• Above two charts are from the same study with the Y axes set to span different ranges (part-to-part/study variation vs. tolerance band)
What if a Gage R&R Study fails? – Root Cause Analysis Tools, Scenarios

• What is the potential issue?
  1. Outlier – operator 2, sample 3: repeatability issues
  2. Reproducibility issues

• What are the potential root causes?
  Typo (can only be removed from dataset if proven), operator error/fatigue, sample geometry, measurement method

• How could the measurement system be improved?
  Verify sample geometry. Verify if measurement procedure needs to be improved. Re-measure.
What if a Gage R&R Study fails? – Root Cause Analysis Tools, Scenarios

• What is the potential issue?
  Data points from operator “EM” see significantly more variation when compared to those from operator “TN”

• What are the potential root causes?

• How could the measurement system be improved?
  Provide adequate training. Improve measurement procedure to be more specific.
What if a Gage R&R Study fails? – Root Cause Analysis Tools, Scenarios

- What is the potential issue?
  1. Repeatability – too much trial-to-trial variation
  2. Reproducibility – difference between operator averages too big

- What are the potential root causes?
  1. Too much inherent measurement system variation
  2. Operator training, skills

- How could the measurement system be improved?
  Provide adequate training.
  Measurement system may not be suitable for application. Improvements to current system or implement new system.
Guard banding is used for mitigating risks associated with measurement uncertainty to protect against consumer’s risk.

- Guard band applied around specification limits
- Guard band width equal to or a fraction of measurement uncertainty
- Should be carefully considered as it effectively reduces the acceptance limits – potentially significant yield loss

What if a Gage R&R Study fails? – Guard Banding

%Tolerance = 25%
Takeaways

• Know your metrics

• Know your measurement application and pick your metric accordingly

• Look for patterns of variation

• Identify root causes, improve measurement system if necessary

• Determine risks associated with measurement uncertainty

Any Questions?

Gabor A. Szabo, CQE
(626) 733-5279
gabor.attila.szabo@gmail.com
Our Planning/Leadership Team

C.G. Mistry
Role: Deputy Regional Director, ASQ Region 7
#SCQC Committee Chair
mistrycg@yahoo.com

Jean Tedrow
Role: Treasurer, ASQ San Gabriel Valley (0702)
#SCQC Committee Treasurer, Finance
jeanflores1988@yahoo.com

Nagesh Malhotra
Role: Vice Chair, ASQ San Gabriel Valley (0702)
#SCQC Marketing Chair
nmalhotra1999@gmail.com

Chen Low
Role: Arrangements Chair, ASQ Los Angeles (0700)
#SCQC Arrangements Chair
chenlow_88@hotmail.com

Brijesh Patel
Role: Chair, ASQ San Gabriel Valley (0702)
#SCQC Technology and Registrations Chair
bradpatelbme@gmail.com

Vinay Goyal
Role: Membership Chair, ASQ San Gabriel Valley (0702)
#SCQC Leadership Committee, Vice-Chair
vinaygoyal@sbcglobal.net

Akhilesh Gulati
Role: Programs Chair, ASQ San Gabriel Valley (0702)
#SCQC Programs Chair
gulati@pivotmc.com

Ron Lombrano
Role: Chair-Elect, ASQ Los Angeles (0700)
#SCQC ASQ 0700 Representative
Ronald_A_Lombrano@raytheon.com

Chris Alexander
Role: Owner, Synergy Executive Education
#SCQC Special Advisor
calexander@synergyteampower.com

Jamie Marks
Role: Chair, ASQ San Fernando Valley (0706)
#SCQC ASQ 0706 Representative
eimajine@att.net
The Arrangements Team

Chair: Chen Low

Volunteers:
James Alexander
Ron Lombrano
Harry Oei
Stanley Lim
Armen Yeghioan
Jamie Marks
Mandana Lotzar
Lilian Ore
To ALL ATTENDEES, SPONSORS AND VOLUNTEERS,
Without each of you, this event would not be a success.
Your contributions, time, and efforts are greatly appreciated.

The SCQC Leadership Team