Evaluation of an attributive measurement system in the automotive industry

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Abstract. Measurement System Analysis (MSA) is a critical component for any quality improvement process. MSA is defined as an experimental and mathematical method of determining how much the variation within the measurement process contributes to overall process variability and it falls into two categories: attribute and variable. Most problematic measurement system issues come from measuring attribute data, which are usually the result of human judgment (visual inspection). Because attributive measurement systems are often used in some manufacturing processes, their assessment is important to obtain the confidence in the inspection process, to see where are the problems in order to eliminate them and to guide the process improvement. It was the aim of this paper to address such an issue presenting a case study made in a local company from the Sibiu region supplying products for the automotive industry, specifically the bag (a technical textile component, i.e. the fabric) for the airbag module. Because defects are inherent in every manufacturing process and in the field of airbag systems a minor defect can influence their performance and lives depend on the safety feature, there is a stringent visual inspection required on the defects of the bag material. The purpose of this attribute MSA was: to determine if all inspectors use the same criteria to determine “pass” from “fail” product (i.e. the fabric); to assess company inspection standards against customer’s requirements; to determine how well inspectors are conforming to themselves; to identify how inspectors are conforming to a “known master,” which includes: how often operators ship defective product, how often operators dispose of acceptable product; to discover areas where training is required, procedures must be developed and standards are not available. The results were analyzed using MINITAB software with its module called Attribute Agreement Analysis. The conclusion was that the inspection process must be improved by operator training, developing visual aids/boundary samples, establishing standards and set-up procedures.

1. Basics of Measurement System Analysis (MSA)
A successful quality improvement or statistical process control program needs good measurement systems. A measurement system is the collection of operations, procedures, gages and other equipment, software and personnel used to assign a number/grade (qualitative, classification) to the characteristic being measured/categorized; the complete process used to obtain measurements. A gage (gauge) is any device used to obtain measurements; frequently used to refer specifically to the devices used on the shop floor; includes go/no-go devices [1].

In order to improve processes, it is necessary to collect data on the "critical to" characteristics of the products. When there is variation in this data, it can either be attributed to the characteristic that is being measured/categorized and to the way that “measurements” are being taken/categorized; this is
known as measurement error. When there is a large measurement error, it affects the data and may lead to inaccurate decision making. It is important to identify the amount of error and the sources of error (each component of the measurement system represents a potential source of error). This can only be done by evaluating the measurement system with statistical tools and the only way to do this is to perform a Measurement System Analysis; MSA is a mathematical procedure to quantify variation introduced to a process or product by the act of measuring and falls into two categories: attribute (for discrete data) and variable (for continuous data). MSA is applicable in 98% of projects and it alone can have a massive effect on the success of any project and improvements within an organization [2].

Measurement System Analysis is important to: study the % of variation in a process that is caused by the measurement system; compare measurements between operators (appraisers, inspectors); compare measurements between two (or more) gages; provide criteria to accept new measurement systems (consider new gage); evaluate a suspect gage; evaluate a gage before and after repair; determine true process variation; evaluate effectiveness of a training program [2].

So, the purpose of MSA is to assess the error due to the measurement systems. The error can be partitioned into specific sources [1]:

- precision (relates to the spread of the data) segmented into: repeatability (within an operator or piece of gage) and reproducibility (operator to operator or attribute gage to attribute gage);
- accuracy (relates to how close the average of the data are to a master value) segmented into: stability (accuracy over time), linearity (accuracy throughout the measurement range), resolution and bias (off-set from master value); a master or a reference is a standard that is used as a reference in a calibration process.

The primary contributors to measurement system error are repeatability and reproducibility. Repeatability is the variation in measurements obtained with one measuring device (gage) when used several times by an operator while measuring the identical characteristic on the same part. Reproducibility is the variation in the average of the measurements made by different operators using the same measuring device (gage) when measuring the identical characteristic on the same part [1].

A gage R&R, which stands for gage repeatability and reproducibility, is a statistical tool that is applied to measure the amount of variation in the measurement system which arises from the people taking the measurement (operator, appraiser, inspector) and the measurement device. The purpose of conducting gage R&R study is to quantify measurement error and to reduce the measurement system variation if it is excessive. In a typical gage R&R study, several appraisers each measure a selected set of items (parts, products) more than once.

2. About attribute measurement system analysis (attribute gage R&R)

The variable gage R&R study, as it applies to continuous data, is widely used and written about. But another form of this tool, the attribute gage R&R (attribute MSA), that is a study comparing categories as opposed to measurements, can improve process yields and reduce costs dramatically. Most processes require at least some form of subjective (visual) inspection or validation [3].

The visual inspection of products involves a lot of problems. The most mattering of them is the one of the important variation of the results of inspection, leading decisions on the conformity of the product sometimes totally opposed. The principal difficulty is that human is the only measuring device which can be used for this type of inspection. Each appraiser must inspect the part and judge the conformity. Consequently, the subjectivity of measure (the human judgment) is very present and the variability therefore high, [4].

Most problematic measurement system issues come from measuring attribute data in terms that rely on human judgment such as good/bad, pass/fail, etc. This is because it is very difficult for all appraisers to apply the same operational definition of what is “good” and what is “bad.” However, such measurement systems are seen throughout industries so it is important to quantify how well such measurement systems are working [5].

The purpose of an attribute MSA is [2]:

- to determine if all inspectors use the same criteria to determine “good” from “bad”;

...
• to assess organization inspection standards against customer’s requirements;
• to determine how well inspectors are conforming to themselves;
• to identify how inspectors are conforming to a “known master,” which includes: how often they ship defective product and how often they dispose of acceptable product;
• to discover areas where: training is required, procedures must be developed and standards are not available.

The concept of R&R studies are the same for attribute data as for variable data, but the measurement of these is entirely different. Attribute gage R&R study looks at how effective or capable an appraiser is in accepting good products and sorting out bad products repeatedly and also looks at the probability of a bad product being missed (a wrong classification) and a good product being rejected (a false alarm).

The methodology for conducting an attribute R&R study is [5]:

Step 1: select at least 20 products (more is preferable, usually between 20 to 30) from the process, that should represent the full spectrum of process variation; for maximum confidence, a 50-50 mix of conforming/non conforming products is recommended but a 30:70 ratio is acceptable.

Step 2: have a master appraiser (expert) which rates each test products into its true attribute category (true status), classifying it as “OK/C/Y/G” for conforming products and “NOK/NC/N/NG” for non-conforming.

Step 3: select the number of appraisers (two or more) and number of trials (two or more checks per product per appraiser) to be conducted

Step 4: inspectors rate (categorize) each part, independently and in a random order, without knowing the master results and record the classification result in data sheet.

Step 5: calculate some measures (scores, statistics), defined as follow:

- Inspector score / Individual Repeatability / Within Appraiser (in Minitab) analyzes how consistent operators are by measuring various products more than once;
- Agreement sau Concordance (with standard) / Individual Effectiveness / Each Appraiser vs. Standard (in Minitab) analyzes the ability of the operators to not only be consistent but also correct in their judgments;
- Disagreement OK/NOK (Wrong Classification, False positive or Miss) is the chance of not rejecting a non conforming products; this is a serious type of error since a non conforming product is accepted;
- Disagreement NOK/OK (False Alarm or False negative) is the chance of rejecting a conforming products; this type of error is not as serious as a miss, since a conforming product is rejected;
- Disagreement mixed (Mixed);
- Between inspectors / Reproducibility of Measurement System / Between Appraisers (in Minitab) analyzes the differences between operators when measuring the same parts and represents the agreement percentage between different appraisers;
- All inspectors vs standard / Overall Effectiveness of Measurement System / All Appraisers vs Standard (in Minitab) represents the overall agreement percentage of both within and between appraisers; it reflects how precise the measurement system performs.

The key in all measurement systems is having a clear test method and clear criteria for what to accept and what to reject. The attribute MSA consists mainly of qualitative/classification counting and division, and the results are evaluated using criteria from table 1 [1]. For any marginally acceptable or unacceptable measurement system, corrective action is required and when corrective action is completed, the attribute MSA must be redone.

Table 1. Decision criteria.

| Measures | Acceptable | Marginally acceptable | Unacceptable |
|----------|------------|-----------------------|--------------|
| Inspector score / Individual Repeatability / Within Appraiser | > 90% | 80% to 90% | < 80% |
### Agreement sau Concordance / Individual Effectiveness / Each Appraiser vs. Standard

| Disagreement OK/NOK (Wrong Classification, False positive or Miss) | > 90% | 80% to 90% | < 80% |
|---|---|---|---|
| Disagreement NOK/OK (False Alarm or False negative) | < 2% | 2% to 5% | > 5% |
| Between inspectors / Reproducibility of Measurement System / Between Appraisers | > 90% | 80% to 90% | < 80% |
| All inspectors vs standard / Overall Effectiveness of Measurement System / All Appraisers vs Standard | > 90% | 80% to 90% | < 80% |

### 3. Case study

Visual inspection is a key quality process in many manufacturing companies. In airbag system manufacturing this process has more importance by reason of many safety features that must detect during visual inspection.

#### 3.1. About the airbag system

The airbag system is a safety device designed for modern vehicles, required to inflate quickly in the case of a collision, preventing the passengers from crashing onto the car’s interior. The airbag system is among the most important automotive safety products. There are 2 main types of airbag systems (Figure 1): frontal airbags subdivided into driver (1), passenger (1) and lower-body protection (2) airbags (knee and anti-sliding) and side-impact airbags subdivided into the following categories: roof-mounted side, door-mounted side (4) and seat-mounted (3) airbags [6], [7], [8].

![Figure 1. Types of airbag systems [7].](image1)

A typical airbag system consists of an airbag module, crash sensors, a diagnostic monitoring unit, a steering wheel connecting coil and wiring and connectors. There are four main parts in an airbag module [8]: an inflator with an initiator, that inflate the folded bag; a bag itself made of thin textile material; a housing (made of steel, plastic or textile material) to store the folded bag and the inflator; a cover (in the steering wheel center for driver airbags) that opens as the bag inflates. For the production of an airbag module, the following components are needed: textile material (i.e. the fabric) for bag and housing, silicone, pigment, sewing thread, metallic and plastic components.

Inspection of textile materials includes examination of physical, mechanical and aesthetic properties. Most important requirements of an airbag fabric are [9]: high tensile and tear strength, low air permeability, good heat capacity and folding behavior, better energy absorption, good coating adhesion, functionality at extreme hot and cold conditions, package ability, reduced skin abrasion, good heat stability and free textile material defects.
Thus, a rigorous quality inspection starting from the yarns used in weaving to the final sewing operation is absolutely necessary. Nylon is widely used in airbag manufacture. Nylon yarns are woven together to produce the airbag fabric. The woven fabrics are then cut and sewn to the required size and shape, depending on the vehicle. The size of the airbags, weave patterns and sewing geometry varies depending on the application, such as driver side airbags, passenger side airbags, side curtains, etc. Traditionally most airbag fabrics were coated with an elastomeric material, such as neoprene or silicone (Figure 2) [7].

3.2. Attribute MSA for airbag fabric

As in other industries, the goal of the automotive industry is to manufacture defects free products. Defects are inherent in every manufacturing process and the quality inspection is, obviously, extremely important for airbag system, especially in the areas of propulsion, static and dynamic inflation and also in the area of fabric quality because even a minor defect can influence airbag system performance and many lives depend on the safety feature.

A common problem in the airbag manufacturing are fabric defects, which could cause complaints from customers or problems in downstream processing. These defects occur with a broad diversity in form and size and are considered major. As it is known the defects of the woven fabrics are resulted from the quality of the yarn or weaving operation. There are very common faults in the woven fabrics which should be identified and removed from the fabrics. These faults include broken ends, missing pick, double end, double pick, oil stain and big knots and so on. However, these problems should be avoided as much as possible during spinning and weaving. Due the mechanics of the weaving machine, some defect types are more likely to occur than others, while the typical size of single defects in fabric images ranges from few millimeters (1-2 mm²) to several centimeters (1-2 cm²) [10].

In the majority of textile factories, the quality fabrics are inspected and monitored by human vision, too. Due to the high importance of this job, this should be done with high accuracy and confidence. In order to evaluate how effective or capable are the appraisers of inspecting the airbag fabric defects, this study presents an attribute MSA made in a local company from the Sibiu region, considering the weaving process and its different types of defects. The inspection results were processed using MINITAB software [11] and are presented from figure 3 to figure 7.

![Minitab worksheet, Individual Repeatability and Individual Effectiveness graphs](image)

Figure 3. Minitab worksheet, Individual Repeatability and Individual Effectiveness graphs
Within Appraisers

Assessment Agreement

| Appraiser | # Inspected | # Matched | Percent | 95% CI    |
|-----------|-------------|-----------|---------|-----------|
| 1         | 50          | 44        | 88.00   | (75.69, 95.47) |
| 2         | 50          | 47        | 94.00   | (83.45, 96.75) |
| 3         | 50          | 43        | 86.00   | (73.26, 94.18) |

# Matched: Appraiser agrees with him/herself across trials.

Each Appraiser vs Standard

Assessment Agreement

| Appraiser | # Inspected | # Matched | Percent | 95% CI    |
|-----------|-------------|-----------|---------|-----------|
| 1         | 50          | 41        | 82.00   | (68.56, 91.42) |
| 2         | 50          | 46        | 92.00   | (80.77, 97.70) |
| 3         | 50          | 39        | 78.00   | (64.04, 88.47) |

# Matched: Appraiser's assessment across trials agrees with the known standard.

**Figure 4.** Individual Repeatability and Individual Effectiveness.

![Image](https://example.com/image1.png)

This is the percent each operator judged a sample GOOD when it was actually BAD (accuracy).

This is the percent each operator judged a sample BAD when it was actually GOOD (accuracy).

Assessment Disagreement

| Appraiser | # OK / NOK | Percent | # NOK / OK | Percent | # Mixed | Percent |
|-----------|------------|---------|------------|---------|---------|---------|
| 1         | 1          | 4.55    | 2          | 7.14    | 6       | 12.00   |
| 2         | 1          | 4.55    | 0          | 0.00    | 3       | 6.00    |
| 3         | 2          | 9.09    | 2          | 7.14    | 7       | 14.00   |

# OK / NOK: Assessments across trials = OK / standard = NOK.
# NOK / OK: Assessments across trials = NOK / standard = OK.
# Mixed: Assessments across trials are not identical.

**Figure 5.** Assesment disagreement.

![Image](https://example.com/image2.png)

This is the percent of samples that were measured differently both times they were measured (precision).

Between Appraisers

Assessment Agreement

| # Inspected | # Matched | Percent | 95% CI    |
|-------------|-----------|---------|-----------|
| 50          | 34        | 68.00   | (53.30, 80.43) |

# Matched: All appraisers' assessments agree with each other.

**Figure 6.** Reproducibility of Measurement System.
Analysing the study results, the conclusion is as follows:

- **Individual Repeatability** of appraiser 1 is 88% and 86% for appraiser 3, so marginally acceptable; this means that appraiser 1 and 3 are only consistent with themselves 88 and 86 percent of the time, so they need retraining; referring to appraiser 2, he’s two assessments agreed with each other about 94% of the time so acceptable;

- **Individual Effectiveness** of appraiser 1 is 82% (marginally acceptable) and only 78% for appraiser 3 (unacceptable); this means that appraiser 1 is in agreement with the standard 82 percent of the time and appraiser 3 only 78 percent of the time, so they need retraining;

These two metrics presented in figure 2 and 3 shows that two of the appraisers disagreed frequently with the right answer, so there was a problem with appraiser 1 and 3.

- **Assessment Disagreement** adds some useful information.
  - Appraiser 1, on 1 occasion classified a non-conforming product as a conforming and on 2 occasions did he classify a conforming as a non-conforming product; the mixed column shows 6 other occasions when he was inconsistent in his judgment.
  - Appraiser 3, on 2 occasions classified a non-conforming product as a conforming and on 2 occasions did he classify a conforming as a non-conforming product; the mixed column shows 7 other occasions when he was inconsistent in his judgment.
  - Appraiser 2 classified a non-conforming as a conforming product on 1 occasion and he did not assess a conforming product as a non-conforming, but the mixed column shows 3 occasions when he was inconsistent in his judgment.

- **Reproducibility of Measurement System**, shows that all three inspectors agree with each other on both assessments only 68 percent of the time, so on only 34 out of 50 fabric inspected. They may not be all using exactly the same operational definition for conforming/non-conforming all the time or may have a very slight difference in interpretation of what constitutes a conform product and a non-conform product.

The last metric, overall Effectiveness of the Measurement System tells that for only 34 out of 50 fabric inspected, all three inspectors agree with the standard, so on only 68 percent of the time. The results show that there is a problem with the ability of the inspectors, especially appraiser 1 and 3, to assess carefully the airbag fabric. So, even trained appraisers cannot see all defects and ways of improving this situation are always under consideration.

Visual inspection of airbag fabric can be improved by:

- appraiser training;
- develop visual aids/boundary samples (Figure 8);
- establish standards;
- establish evaluation procedures.

4. **Conclusion**

An attribute gage R&R can normally be performed at very low cost with great impact on any quality improvement process. By understanding existing measurement systems a team can better understand the data provided by those systems and make better business decisions.
a) Knot: maximum diameter - 3 mm, maximum frequency - 2; minimum separation distance - 500 mm

b) Broken ends

c) contamination with dirt: maximum diameter - 15 mm; maximum frequency - 2 to 10 on 400 cm²

Figure 8. Visual aids.
Periodic appraiser training along with developing visual aids and establishing evaluation procedures (evaluation of the same location on each part, each evaluation performed under the same lighting and ensure all evaluations are made with the same standard) are critical to ensure visual inspection methods remain consistent.

Attributive measurement systems are often used in some manufacturing processes, so their assessment is important to obtain the confidence in the inspection process, to see where are the problems in order to eliminate them and to guide the process improvement.

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