EVALUATION OF THE MEASUREMENT SYSTEM PRECISION - BASIC COMPONENT IN THE QUALITY CONTROL PROCESS

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Abstract: The use of measurement system Repeatability and Reproducibility (R&R) studies is widespread in abroad industry. Such analyses have become mandatory for many companies who supply the automotive industry and is now an integral part of the QS 9000:1998 and ISO/TS 16949:2002 automotive industry standards. It is the aim of this paper to address such issues and to show a measurement system R&R case study that was made in a major local automotive company.

1. MEASUREMENT SYSTEM ANALYSIS

Measurement systems are used every day in manufacturing, research and development, sales and marketing. Measurement systems are a critical component in the quality a company provides to its customers and they represent a significant investment. Measurement systems are essential to the quality of a manufacturing process because the measurement process itself is subject to variation, and excessive variation in the measurement systems can mask critical variation in the manufacturing process. Measurements are the window through which we look at products and processes, and it is necessary to know whether the image we see are accurate or, perhaps, somewhat distorted. Often measurements are made with little regard for the quality of such measurements. Yet all too often, the measurements are not representative of the true value of the characteristic being measured. That might be because the measurement system is not accurate enough or not precise enough. The moral is that before one embarks on using a new measurement system for a characteristic which has not been previously measured on it, it should perform a measurement system analysis, because this is critical to the success of every measurement and ensure that future measurements will be representative of the characteristic being measured [1], [7].

Measurement System Analysis (MSA) is a statistical tool used to analyze the variation in measurement test equipment & measurement systems. MSA studies will be performed on specified part characteristics and it is strongly recommended that MSA studies be applied on part characteristics deemed safety critical or critical, part characteristics that contain a poor customer or in-house history record (e.g. low Cpk), part characteristics that are difficult to measure or that have very tight tolerances. MSA evaluates if a measurement system is suitable for a specific application and it is useful not only to audit existing measurement systems, but also to select the most appropriate ones for a new measurement task.

2. REPEATABILITY AND REPRODUCIBILITY CONCEPTS

There are number of factors that affect the ability of a measurement system to discriminate among the units it measures. These factors can be categorized generally into those that affect central location and those that affect the variability (spread) of the measurements. Variability factors measured by repeatability and reproducibility - these terms refer to the precision of a measurement system - (fig.1) are the more familiar, while factors related to the central location of the measurements: stability, bias, and linearity (they refer to the accuracy of a measurement system) are relatively new approaches. Both approaches may need clarification. Accuracy is defined as the closeness of agreement between observed values and a known reference standard, while precision is a measure of the closeness between several individual readings [2], [3], [4].

So precision or measurement variation is a measure of the degree of repeatability between measurements. Precision is often denoted by $\sigma_{R\&R}$, which is the standard deviation of the measurement system. The smaller the spread of the distribution, the better the precision. Precision can be separated into two components, which are related as follows:

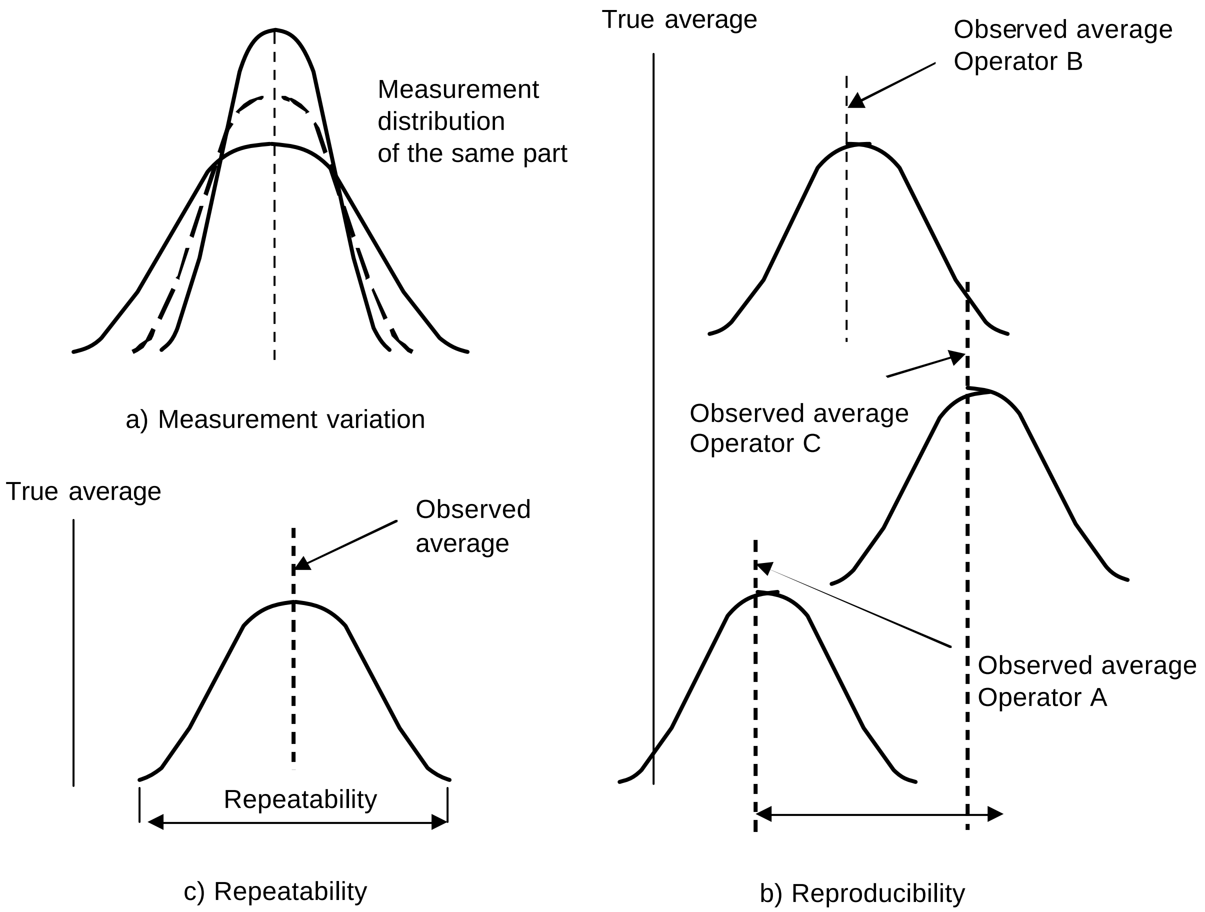

Figure 1: Measurement variation and its two components

- Repeatability or equipment variation refers to the variation in measurements observed when one operator repeatedly measures the same characteristic in the same place on the same part with the same measurement tool (i.e. variation in measurements under identical conditions); it is the inherent variation within the measurement tool and it is represented by $\sigma_{repeatability}$, which is the standard deviation of the measurement tool.

- Reproducibility or appraiser/operator variation refers to the difference in the average of the measurements observed when different operators measure the same parts using the same measurement tool and it is represented by $\sigma_{reproducibility}$; it is due to factors other than the machine variation, such as, but are not limited to, operators, temperature, humidity, and part fixturing technique.

R&R study allows one to estimate the contribution of variation attributable to the measurement system itself and is used to ensure that a company measurement system is acceptable. If the measurement system R&R study indicate that the recorded measurements may be unreliable, this may impact all subsequent analyses, e.g. control charts, capability analyses etc.

Often, an evaluation of a measurement system should be performed using a measurement system repeatability and reproducibility study, so the amount of variability in a set of measurements taken on a single measurement tool that can be attributed to the measurement tool itself (repeatability) and to the entire measurement system (reproducibility) must be determined [1], [4], [5], [7].

There are a number of procedures, which are widely used, in the automotive and other industries to analyze measurement systems. A typically study utilizes one to three appraisers (m) for one measuring tool that is measuring a single characteristic. Each appraiser measures five to ten parts (n) selected from a process two or three times (r). Before proceeding with the analysis of the study, the ranges for the replications of the measurements made by each appraiser on each part are determined and used to calculate control limits for the range chart. Then each range is checked to determine if it falls inside the limits. Those measurements that result in a range outside the limits should be excluded from further analysis or should be redone. Once the basic calculations are made, an analysis of repeatability and reproducibility can be performed [1], [6], [7].

To interpret the measurement system R&R study, we looked at the percentage of the part tolerance that measurement system error consumes or the percentage of total variation that's due to measurement system error. Generally, manufacturers accept percentages expressed as a percent of the total variability and the following criteria for acceptance are: R&R as a percentage of the total variability is under 10% error – acceptable; R&R as a percentage of the total variability is 10% to 30% error – may be acceptable based upon the importance of the application, cost of measurement tool, cost of repair and so on; R&R as a percentage of the total variability is over 30% - generally not acceptable and every effort to identify and correct the problem should be made.

3. CASE STUDY

A measurement system R&R study was made in a major local company who supply the automotive industry. A measurement system used to measure the bore diameter of a part, having a specification of 18.1 to 18.3 mm, was to be evaluated. The repeatability and reproducibility study collected the data from table 1.

Operative assumptions included: the measuring tool stayed in calibration (central location did not change); operators used the same method of measurement; parts were measured in the same place. If the assumption that the parts are measured in the same place is incorrect, the possibility of within-part variation will need to be considered, too.

Table 1: Repeatability and Reproducibility Report

General data					
Part:	B4-RAO-Z007A05	*Gage name:*	Dial bore gauge	*Date*	05.04.06
Characteristic:	Ø 18.1	*Gage number:*	UMF 135-74		*Prepared by*
Tolerances:	0; +0.2	*Gage type:*	0.002 mm		Simion Carmen
Number of parts	10	*Number of operators*	3	*Number of trials*	3

Obtained values												
OPERATOR	*Trial*	*PART*										
		1	2	3	4	5	6	7	8	9	10	
1 *A*	1	18.152	18.160	18.170	18.152	18.150	18.270	18.198	18.202	18.220	18.232	18.191
2	2	18.152	18.158	18.172	18.156	18.158	18.268	18.198	18.210	18.224	18.220	18.192
3	3	18.154	18.160	18.172	18.154	18.152	18.270	18.198	18.200	18.220	18.220	18.190
4 Mean		18.153	18.159	18.171	18.154	18.153	18.269	18.198	18.204	18.221	18.224	X-bar A=18.191
5 Range		0.002	0.002	0.002	0.004	0.008	0.002	0.000	0.010	0.004	0.012	R-bar A= 0.005
6 *B*	1	18.154	18.162	18.168	18.152	18.158	18.270	18.214	18.212	18.224	18.240	18.195
7	2	18.150	18.164	18.166	18.170	18.170	18.268	18.200	18.210	18.224	18.236	18.196
8	3	18.162	18.160	18.172	18.160	18.168	18.260	18.208	18.202	18.220	18.250	18.196
9 Mean		18.155	18.162	18.169	18.161	18.165	18.266	18.207	18.208	18.223	18.242	X-bar B=18.196
10 Range		0.012	0.004	0.006	0.018	0.012	0.010	0.014	0.010	0.004	0.014	R-bar B= 0.010
11 *C*	1	18.158	18.164	18.170	18.168	18.158	18.276	18.208	18.202	18.230	18.248	18.198
10	2	18.168	18.162	18.170	18.158	18.166	18.260	18.212	18.200	18.240	18.230	18.197
13	3	18.168	18.160	18.180	18.170	18.158	18.270	18.210	18.200	18.232	18.248	18.200
14 Mean		18.165	18.162	18.173	18.165	18.161	18.269	18.210	18.201	18.234	18.242	X-bar C=18.198
15 Range		0.010	0.004	0.010	0.012	0.008	0.016	0.004	0.002	0.010	0.018	R-bar C= 0.009
												X-double bar=18.195
16 Range per part		18.158	18.161	18.171	18.160	18.160	18.268	18.205	18.204	18.226	18.236	Rp= 0.110
		R-double bar=0.008				X-bar Diff=0.007				Uper Control Limit for R=0.021		

Results			
Repeatability	EV=0.025	%EV=13.7	The measuring system may be marginally aceptable based on the importance of the application, cost of the measuring tool, cost of repair and so on; it may require further analysis to find the sources of measurement error.
Reproducibility	OV=0.019	%OV=10.7	
Repeatability & Reproducibility	R&R=0.032	%R&R=17.4	
Part-to-part Variation	PV=0.179	%PV=98.5	
Total Variability	TV=0.182		

After the data are collected, the calculations will be carried out per the following procedure [1], [7]:

- Reproducibility (steps 1-6)

1. For operators data, add up the readings of the 10 parts for the first trial (add horizontally) and divide by 10 to have the average. Enter the average of the 10 readings in the "Mean" box;
2. Repeat with the second and the third trials' data;
3. Add up all three Mean's of three trials and divide by 3 to have the average reading for operator X-bar A;
4. Repeat for the operator B's and C's readings: X-bar B and X-bar C;

5. Examine X-bar A, X-bar B and X-bar C. The smallest of the three is designated as X-bar Min and the largest is X-bar Max;
6. Calculate X-bar Diff=X-bar Max - X-bar Min. Enter it in the "X-bar Diff" box;

- Part Variation (steps 7-10)

7. Calculate the total of all readings for part numbered 1 by adding all part 1's readings from all three operators A,B and C (add vertically). Enter the result in the form;
8. Calculate the average reading for part numbered 1 by dividing the total of part 1's readings by 9 (the number of times part 1 was measured by all three operators).
9. Repeat calculating for the remaining 9 parts.
10. Calculate as the Range of all by subtracting the smallest from the largest. Enter in the form as Rp;

- Repeatability (steps 11-17)

11. In the box for operator A, determine the range of operator A's readings on part numbered 1 by subtracting the smallest of the three readings from the largest. Enter the range as R;
12. Repeat determining the ranges for the remaining 9 parts for operator A. Enter the results horizontally;
13. Calculate the average of the 10 Ranges for operator A by adding up all 10 ranges horizontally and divide by 10. Enter the result as R-bar A;
14. Repeat determining the ranges and calculate average of the ranges for operators B and C. Enter the results as R-bar B and R-bar C;
15. Calculate the average range, R-double bar and enter it in the "R-double bar" box;
16. Calculate the Upper Control Limit for the ranges by multiplying R with constant D_4 which can be found in the table 2;
17. Examine all the individual ranges of the readings (R) of each part for all operators. If any of these ranges is greater than the UCL, they will be marked. The cause of these high ranges should be identified and corrected. Then one of the following two options must be performed:
   a. Repeat these readings using the same operator and parts as originally used and repeat all affected calculations;
   b. Discard those readings and reaverage and recompute ranges and UCL from the remaining readings;

- Estimation of Total Variation

After all immediate calculations are done, the estimates of the total variation of each source of variation final analysis will can be carried out per the following procedure:

Calculate Repeatability (EV), Reproducibility (OV), Combined R&R, Part Variation (PV) and Total Variation (TV) per formulas (1), (2), (3), (4) and (5).

Calculate %EV (6), %OV (7), %R&R(8) and %PV(9) as percentage of TV. The sum of the percent consumed by each factor will not equal to 100%.

$$EV = R - \text{double bar} \cdot K_1 \qquad (1)$$

$$OV = \sqrt{\left[(X\text{-bar Diff} \cdot K_2)^2 - (EV^2/n \cdot r)\right]} \quad (2)$$

$$R\&R = \sqrt{EV^2 + OV^2} \quad (3)$$

$$PV = R_p \cdot K_3 \quad (4)$$

$$TV = \sqrt{R\&R^2 + PV^2} \quad (5)$$

$$\%EV = 100[EV/TV] \quad (6)$$

$$\%OV = 100[OV/TV] \quad (7)$$

$$\%R\&R = 100[R\&R/TV] \quad (8)$$

$$\%PV = 100[PV/TV] \quad (9)$$

Table 2: Adjustment factors

Adjustment factors		
Number of trials	D_4	K_1
2	3.27	4.35
3	2.58	3.05
Number of operators		K_2
2		3.65
3		2.70
Number of parts		K_3
2		3.65
3		2.70
4		2.30
5		2.08
6		1.93
7		1.82
8		1.74
9		1.67
10		1.62

Because measurement system R&R value was between 10% and 30%, it had required further analysis to find the sources of measurement error.

The supposition was that the dial bore gauge was not adequate to measure this bore diameter, because the cylindrical hole goes on with a conic surface and sometimes the contact point of the dial bore gauge (in gauges for measuring bores the head of the gauges has diametrically opposed holes with two measuring balls and two centering balls; centering takes place because the measuring balls are 0.01 mm greater in diameter than the centering balls) come in contact with the conic surface of the part not with the cylindrical part of the bore, and so the measurements are inexact.

The decision was to replace the dial bore gauge by an internal micrometer and another measurement system R&R study was made (table 3). The new results were:

- Repeatability - Equipment Variation=6.39%
- Reproducibility - Operator Variation=3.59%
- Repeatability and Reproducibility - Equipment & Operator Variation=7.33%

The conclusion was that the new measuring system is acceptable (excellent).

Table 3: Repeatability and Reproducibility New Report

General data					
Part:	B4-RAO-Z007A05	*Gage name:*	Micrometer	*Date*	06.049.06
Characteristic:	Ø 18.1	*Gage number:*	MAL-149-80		*Prepared by*
Tolerances:	0; +0.2	*Gage type:*	0.005 mm		Simion Carmen
Number of parts	10	*Number of operators*	3	*Number of trials*	3

Obtained values

OPERATOR	*Trial*	*PART* 1	2	3	4	5	6	7	8	9	10	
1 *A*	1	18.150	18.165	18.170	18.165	18.150	18.275	18.205	18.205	18.230	18.245	18.196
2	2	18.150	18.165	18.165	18.165	18.150	18.270	18.205	18.205	18.235	18.240	18.195
3	3	18.145	18.170	18.165	18.154	18.140	18.275	18.205	18.205	18.235	18.245	18.195
4 Mean		18.148	18.167	18.167	18.165	18.147	18.273	18.205	18.205	18.233	18.243	X-bar A=18.195
5 Range		0.005	0.005	0.005	0.000	0.010	0.005	0.000	0.000	0.005	0.005	R-bar A= 0.004
6 *B*	1	18.145	18.170	18.175	18.170	18.140	18.275	18.215	18.205	18.240	18.230	18.197
7	2	18.150	18.165	18.175	18.175	18.145	18.280	18.215	18.210	18.245	18.230	18.199
8	3	18.150	18.165	18.175	18.170	18.145	18.275	18.215	18.205	18.240	18.230	18.197
9 Mean		18.148	18.167	18.175	18.172	18.143	18.277	18.215	18.207	18.242	18.230	X-bar B=18.198
10 Range		0.005	0.005	0.000	0.005	0.005	0.005	0.000	0.005	0.005	0.000	R-bar B= 0.004
11 *C*	1	18.140	18.160	18.165	18.175	18.140	18.275	18.210	18.205	18.230	18.235	18.194
10	2	18.140	18.160	18.165	18.175	18.140	18.285	18.205	18.200	18.235	18.235	18.194
13	3	18.145	18.170	18.170	18.180	18.145	18.275	18.205	18.205	18.235	18.230	18.196
14 Mean		18.142	18.163	18.167	18.177	18.142	18.278	18.207	18.203	18.233	18.233	X-bar C=18.195
15 Range		0.005	0.010	0.005	0.005	0.005	0.010	0.005	0.005	0.005	0.005	R-bar C= 0.006
												X-double bar=18.196
16 Range per part		18.146	18.166	18.169	18.171	18.144	18.276	18.209	18.205	18.236	18.236	Rp= 0.132
		R-double bar=0.005				X-bar Diff=0.003				Uper Control Limit for R=0.012		

Results

Repeatability	EV=0.014	%EV=6.39	The measuring system is acceptable
Reproducibility	OV=0.008	%OV=3.59	
Repeatability & Reproducibility	R&R=0.016	%R&R=7.33	
Part-to-part Variation	PV=0.214	%PV=99.7	
Total Variability	TV=0.215		

4. CONCLUSION

The purpose of the presented repeatability and reproducibility study was to allow the quality control engineer to assess the precision of the measurement system used in this quality control process.

Obviously, if the measurement system is not repeatable (large variability across trials) or reproducible (large variability across operators) relative to the variability between parts, then the measurement system is not sufficiently precise to be used in the quality control efforts. For example, it should not be used in charts, or product capability analyses and acceptance sampling procedures. Identifying and reducing measurement variation was the whole reason for doing measurement system repeatability and reproducibility study.

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