



Measurement System Analysis for improved manufacturing processes in a Job-shop

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ABSTRACT: Important decisions in the manufacturing sector are heavily reliant on the capabilities of the measurement system in place because faulty data collection can make it difficult to detect an out-of-control manufacturing process and also, to distinguish between acceptable and unacceptable products. Therefore, the objective of this study is to conduct a measurement system analysis (MSA), to improve manufacturing processes in a Job-shop. Deploying standardized methods for a Gage Repeatability and Reproducibility (Gage R&R) study and with the support of the Minitab Statistical software package, the Gage Repeatability and Reproducibility (GR&R) was found to be 19.56% (required GR&R < 30%) with the number of distinct categories (ndc) obtained to be 7 (required ndc ≥ 5), indicating that the manufacturing process can rely on data accuracy from the measuring system put in place. This shows that a Gage R&R study has the potential to improve data reliability, improve manufacturing processes and also, reduce cost associated with rework or scrap, and we strongly recommend the MSA study using Gage R&R to every manufacturing organization for its many benefits.

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Measurement of the products and measurement of the processes are the two types of measurements used in a manufacturing setting to confirm quality and measure performance (R. R. Smith, McCrary, and Callahan 2007). Therefore, precise and accurate measurement procedures are necessary for both process optimization and product evaluation. Understanding and controlling measurement error, also known as Measurement Systems Analysis (MSA), is a crucial task in manufacturing process improvement since all measurements have error margins (R. R. Smith, McCrary, and Callahan 2007; Montgomery 2009; Kesiena Ezewu, Amagre, and Abovie 2023). Auditing and accepting a measuring

system can be very important because the accuracy of the measurements tells line operators when they need to make changes to keep the manufacturing process running within the tolerance limits that have been set previously. A gage repeatability and reproducibility study (GR&R) may identify if the measurement equipment, personnel or manufacturing process is responsible for the overall variability seen in a process.

The measurement system's benefit is low when the data quality is low, and it is high when the data quality is high. This makes it easier to distinguish between parts that are in and out of specification,

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enabling parts to be approved or declined with more assurance (R. R. Smith, McCrary, and Callahan 2007; Plura *et al.* 2023).

In addition to topics like Statistical Process Control, Capability Analysis, and gauge repeatability and reproducibility studies, MSA offers a full set of instruments for the measurement, approval, and analysis of data and errors (Soares *et al.* 2022). MSA is aware that measurements are taken on various items using both tangible tools and visual examination, which depends on human assessment of the features and attributes of the finished product.

A measurement system's efficacy is dependent on having precise gauges and using them correctly. Common measurement tools like the calipers and micrometers used in this case study can be particularly harmful if not handled properly (Hewson, O'Sullivan, and Stenning 1996). Gage repeatability and reproducibility (Gage R & R) is an industry-standard technique to evaluate measurement equipment for precision; repeatability refers to an instrument's innate capacity to display the same value of measurement when operated by the same person/appraiser, while reproducibility refers to the variation of the measurement resulting from the measurement carried out by different persons (Soares *et al.* 2022; Alban and Musset 2025). To achieve greater confidence in the reliability of data collected, measuring tools must be appropriate for intended use and manufacturing processes need to be adequately controlled (Soares *et al.* 2022; Alban and Musset 2025; Kesiene Ezewu, Amagre, and Chuks 2024; Montgomery 2009). Measurement repeatability and reproducibility were highly valued by the automotive and electronics industries in the 1980s, and their employment of Gage R&R studies was encouraged (Snee 2021). In the field of Gage R & R, which is the focus of the current work, applied research can be either destructive (Sharma, Sahni, and Sharma 2019; Soares *et al.* 2022; Cepova *et al.* 2018) or nondestructive (Cepova *et al.* 2018; Peruchi *et al.* 2013; Liangxing, Wei, and Liang 2014; Barbosa, Peres, and Hermosilla 2014; Wrzochal and Adamczak 2019). Gauge R & R has been used by a number of authors for certain objectives, such as managing the human elements related to measuring mistakes (Besterfield 2004). In order to assess whether a gauge is suitable for a given application (Burdick, Park, and Montgomery 2005), to improve measurement procedures, and to operate as an audit tool for personnel and manufacturing processes (Wesff 2012; Dasgupta and Murthy 2001; Smith *et al.* 2005). Additionally, to identify the primary causes of measurement variation (Soares *et*

al. 2022; Lupan and Bacivarof 2005; Wrzochal and Adamczak 2019). Thus, the goal of this study is to conduct a measurement system analysis to improve manufacturing processes in a Job-shop.

MATERIALS AND METHODS

The chosen measured part for the experiment was the length of 10d nails produced in the factory. According to ASTM standards, 10d nails have recommended length of 76.2mm with tolerance limits of ± 2.38 mm (ASTM. 2005). Parts for the measurement analysis were randomly collected from the 10d nail making machine. To conduct this MSA study, 20 parts (Nails) randomly selected were given to 3 machinists/operators in a run-order based on a crossed experimental model (Crossed Gage R & R) generated by the Minitab statistical software package. This guarantees that the assessors do not recall their previous measurements, that each measurement is independent of the previous measurement, that interactions between operators and the measured nail length are mapped, and that they should not witness other assessors measuring the parts (Sharma, Sahni, and Sharma 2019). The sample size of twenty pieces, three assessors, and two measurements ($20 \times 3 \times 2 = 120$) was obtained from the three separate assessors who measured the length of these 20 nails twice. This meets the standards for a Gage R & R study (Soares *et al.* 2022; Sharma, Sahni, and Sharma 2019). An I.S.O.-certified digital vernier caliper prepared for data gathering is depicted in Figure 1.



Fig 1: Digital vernier caliper for data collection.

One of the main challenges in a manufacturing process is accurately measuring process variation in order to identify opportunities for improvement and satisfy customer needs (Cepova *et al.* 2018). Both process variability and measuring system variability contribute to a system's overall variability. The standard deviation of measurement errors (σ_e) is calculated using equation (1) (Mitra 2016):

$$\sigma_e = \sqrt{\sigma_t^2 + \sigma_p^2} \quad (1)$$

Also, the measured observations (σ_m) have a standard deviation expressed in equation (2);

$$\sigma_m = \sqrt{\sigma^2 + \sigma_e^2} \quad (2)$$

Where σ_t^2 and σ_p^2 represents repeatability and reproducibility of the variance observed respectively, while σ^2 represents the process variance.

A common measure is the proportion of total variance consumed by the measurement system for repeatability and reproducibility, known as percentage repeatability and reproducibility (%R&R) is derived using equation (3) (Cepova *et al.* 2018; Mitra 2016);

$$\%R\&R = \frac{\sigma_e}{\sigma_m} \times 100 \quad (3)$$

Acceptable values should be %R&R<30% but most desirable values are %R&R<10%.

Another crucial statistic that compares the variance in the measurement system to the tolerance spread is the precision to tolerance ratio (r), which is represented by equation (4) and is also known as the P/T ratio (Mitra 2016).

$$\frac{P}{T}(r) = \frac{6\sigma_e}{USL - LSL} \times 100 \quad (4)$$

Where USL-LSL represents the manufacturing process tolerance limits. In terms of process variation, the measuring system's variability is represented by the percentage of process variation (%PV), which is determined by equation (5):

$$\%PV = \frac{\sigma_e}{\sigma} \times 100 \quad (5)$$

Where σ represents the standard deviation for the process. We also take an interest in the number of distinct categories (ndc), within the process data that the measurement system can discern or distinguish. It is expressed in equation (6) (Cepova *et al.* 2018);

$$ndc = \frac{\sigma}{\sigma_e} \times 1.41 \quad (6)$$

The desirable number of distinct categories should be ≥ 5 (Cepova *et al.* 2018; AIAG 2002). If the number of distinct categories is < 2 , the measurement system is of no value.

On the basis of the measured observations, the observed capability index (C_p^*) is given by equation (7);

$$C_p^* = \frac{USL - LSL}{6\sigma_m} \quad (7)$$

And the true capability index given (C_p) as a function of the observed capability index (C_p^*) and the precision to tolerance ratio (r) is obtained using equation (8) (Mitra 2016)

$$C_p = \frac{1}{\sqrt{(1/C_p^*)^2 - r^2}} \quad (8)$$

RESULTS AND DISCUSSION

The original data set was collected according to the run order for cross gage R&R study generated by Minitab statistical software for three operators measuring twenty parts twice. In Table 1, we present the mean, range and standard deviation of the measurements obtained from the three operators. We can also observe in Table 3 that the variance of measurements due to the gage system is 0.023807. The process part-to-part variance is 0.598221, while the total variance of measured data is 0.622028. In Table 2, we can observe that the P-value for parts as well as the operator-part interaction is significant (0.000).

Table 1: The mean, range and standard deviation for measurements obtained from operators

Measurement Parameters	Operator 1	Operator 2	Operator 3
Mean	76.10mm	76.05mm	76.13mm
Standard deviation	0.7730	0.7618	0.7994
Range	0.942	0.843	0.947

Table 2: Two-Way ANOVA Table with Interaction

Source	DF	SS	MS	F	P
Parts	19	69.0809	3.63584	78.170	0.000
Operators	2	0.1280	0.06402	1.376	0.265
Parts * Operators	38	1.7675	0.04651	205.20	0.000
Repeatability	60	0.0136	0.00023		
Total	119	70.9900			

a to remove interaction term = 0.05

Table 3: Variance Components for Gage R&R Study

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.023807	3.83
Repeatability	0.000227	0.04
Reproducibility	0.023580	3.79
Operators	0.000438	0.07
Operators*Parts	0.023143	3.72
Part-To-Part	0.598221	96.17
Total Variation	0.622028	100.00
Process tolerance (USL - LSL) = 4.76		

The precision to tolerance ratio (r), as observed in Table 4, is 0.1945 (19.45%), which implies that the

measurement system uses 19.45% of the tolerance spread (Mitra 2016). The metric %R&R, which compares the standard deviation associated with repeatability and reproducibility of the gage system relative to the total variation, is found to be 19.56%. Since %R&R < 30%, therefore, the measurement system is acceptable (Mitra 2016; Soares *et al.* 2022; Wrzochal and Adamczak 2019; Cepova *et al.* 2018). However, improvements may still be possible to reduce it below 10%. Since reproducibility is the larger proportion of the total Gage R&R, extra training may be required to improve the handling of parts by the operators for greater consistency in how they measure the parts. The number of distinct categories is indicated in Table 4 as 7, where desirable values are recommended to be ≥ 5 (Soares *et al.* 2022; Cepova *et al.* 2018; AIAG(b) 2010). The number of distinct categories (ndc) of 7 informs us that the measurement system provides sufficient and reliable data/information about process changes. The part-to-part or process variation shown in Table 4 consumes about 97.49% of the tolerance while accounting for about 96.17% of the variance for part-

to-part shown in Table 3. Therefore, part-to-part is the dominant factor contributing to process variability. Taking a look at the components of variation in Figure 2, Part-to-Part remains the greatest contributor to the overall process variation, and this proves that the measurement system can reliably distinguish between parts. Repeatability is the lowest contributor to overall process variation.

Table 4: Gage Evaluation for the Study

Source	(SD)	Study Var (6×SD)	% Study Var (%SV)	% Tolerance (SV/Toler)
Total Gage R&R	0.154295	0.92577	19.56	19.45
Repeatability	0.015055	0.09033	1.91	1.90
Reproducibility	0.153559	0.92135	19.47	19.36
Operators	0.020922	0.12553	2.65	2.64
Operators*Parts	0.152127	0.91276	19.29	19.18
Part-To-Part	0.773447	4.64068	98.07	97.49
Total Variation	0.788687	4.73212	100.00	99.41
Number of Distinct Categories = 7				

SD = standard deviation

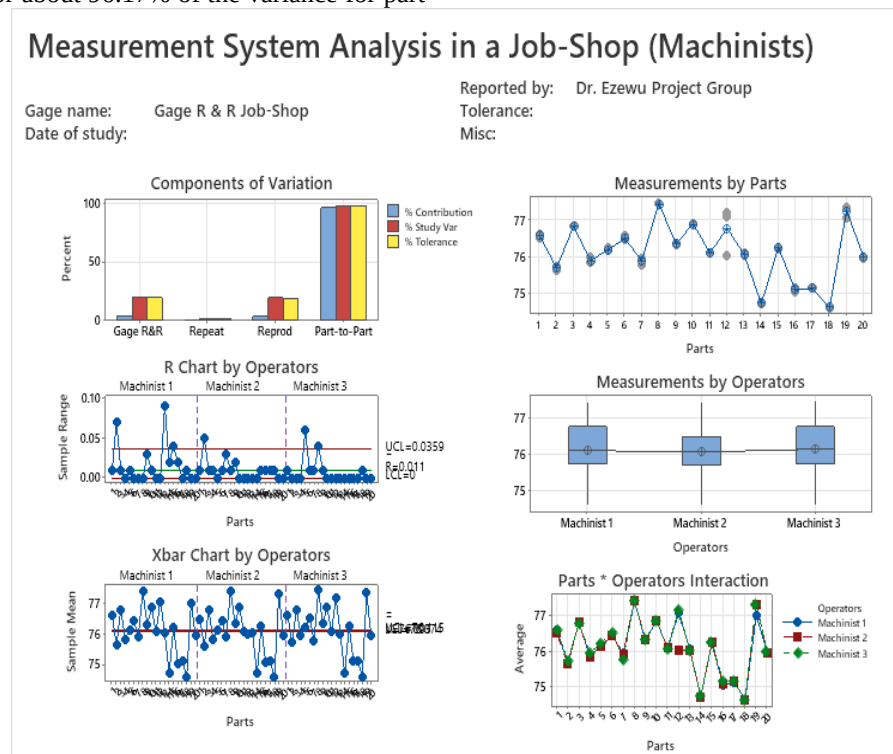


Fig 2: Graphical chart for Gage R&R Study in a Job-Shop

Measurements by the operator's graph indicate that the mean of the operator's measurements is quite close, while the parts-operator interaction shows that the measurements from operators are quite similar overall. Since the X-Bar Chart illustrates the measuring device's discriminating ability and the R-Chart displays the variability in operator readings, the

X-Bar Chart displays all points outside the control limits as anticipated (Mitra 2016). Compared to Operator 1, the measurements of Operators 2 and 3 exhibits less variability within parts. The estimated standard deviation of all measured values is 0.788687 (obtained from Table 4). This gives us the process potential using equation (7);

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$$C_p^* = \frac{USL - LSL}{6\sigma_m} = \frac{4.76}{6 \times 0.7886887} = 1.006$$

A potential process capability of 1.006 shows that the process is barely capable in meeting specification (Mitra 2016). The true process potential, after discounting for the variability in the measurement system, is estimated using equation (8), as we substitute the values for the process potential (C_p^*) and the precision-to-tolerance ratio ($r = 0.1945$).

$$C_p = \frac{1}{\sqrt{(1/C_p^*)^2 - r^2}} = \frac{1}{\sqrt{0.9881 - 0.0378}} = \frac{1}{0.975} = 1.026$$

With the true potential estimated at $C_p = 1$, the manufacturing process is marginally capable and management must strive to reduce the inherent variability in the 10d nail production process.

Conclusion: The main objective for this MSA study using gage R&R was to validate the existing measuring system so that when the measuring system passes the gage R&R test, it gives more confidence that when errors arise in the manufacturing process, they will readily be detected for corrective action. This goes to show that the gage R&R study may be used as a tool to audit/validate operators' ability to obtain accurate/reliable measurements and also as a tool to identify the most important causes for process variation to improve measurements and also reduce errors associated with human personnel. This shows that a Gage R&R study has the potential to improve data reliability and reduce cost in manufacturing as it reduces rework or scrap, and we strongly recommend the MSA study using Gage R&R to every manufacturing organization for its numerous benefits.

Declaration of Conflict of Interest: The authors declare no conflict of interest

Data Availability: The raw dataset is available upon request from the corresponding author.

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