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Review of Gauge Repeatability and Reproducibility for Dimensional Measurements

Joel Arumun[1*], Victor Ekanem[1], Evans Ashigwuike[2]

[1]Alumni, Control Systems and Instrumentation, University of Huddersfield, United Kingdom
[2]Department of Electrical and Electronics Engineering, University of Abuja, Nigeria

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***Corresponding author:** Joel Arumun
Alumni, Control Systems and Instrumentation, University of Huddersfield, United Kingdom

Abstract

Measurement system analysis is crucial in the continuous improvement of manufacturing processes. Gauge Repeatability and Reproducibility (GR&R) is a process of examining the conformity or non-conformity of the major components of a measurement system; tools, equipment, and operators. This reveals the component contributing the most error or variation in the measurement system. This paper reviews GR&R in dimensional measurements with particular emphasis on accuracy, precision and reliability. There is an introduction to metrology and some metrology terminologies to lay the foundation for the appreciation of gauge repeatability and reproducibility. A critical review of some literature on GR&R studies is done and is expanded to cover general dimensional measurement and investigation of two main areas of measurement error in gauges. The effectiveness of a gauge as a measuring tool is crucial in determining the gauge capability thus, this GR&R review.

Keywords: Gauge Repeatability and Reproducibility (GR&R), Measurement Systems. GR&R review.

1.0 INTRODUCTION

Metrology is the science of measurement, and measurement is the language of science [1] and it is used in communicating size, quantity, position, condition and time. It has advanced significantly since using the foot, hand, length of a human stride and other forms of untraceable measurement to quantify length, weight and volume through to the invention of the cubit and subsequently its subdivisions. It has become essential in today's world especially in manufacturing because it establishes standards for measurement used locally, nationally and internationally in science and industry. It can be broadly divided into scientific metrology, technical or industrial metrology, legal metrology and, more recently, virtual metrology.

Very common terminologies used in metrology include accuracy, traceability, uncertainty, precision, repeatability, reproducibility, errors-in-measurement and resolution in national and international standards. This paper intends to narrow its scope to repeatability and reproducibility using the gauge. Some of these terminologies are explained in the paragraphs below.

1.1 Accuracy and Precision

The difference between the real value of a given part and an average of repeated measurements of the same part is termed accuracy. Precision is then defined as the level to which repeated measurements seem to agree with each other. It is getting consistent results repeatedly. Accuracy refers to the long-term average of measurements while precision refers to long-term variation.

1.2 Repeatability and Reproducibility

According to [2], the repeatability of a measuring instrument refers to how well the instrument can repeatedly, measure the same characteristic given the same condition. On the other hand, reproducibility can be defined as the variation due to different operators using the same measuring instrument at varying periods and environmental conditions.

1.3 Traceability

The word "traceability" when used in the context of measurement is called "metrological traceability." Metrological traceability refers to how a measurement can be related to stated references, usually national or international standards through comparisons [3].

Traceability is also defined as "the property of the result of a measurement or the value of a standard that allows that standard to be related to stated references through an unbroken chain of comparisons that possess stated uncertainties" [4]. Quality standards such as ISO 9000 and ISO/IEC 17025 require traceability of all measurements and calibrations performed.

1.4 Uncertainty

Uncertainty of a measurement as defined by [5] is the doubt about the validity of the result of a measurement. This could be discussed in terms of absolute and relative uncertainties but also of importance is that uncertainties could be categorised into type A and type B. [6] defines these two categories according to how their numerical value is estimated. Type A is evaluated by applying statistical methods to several repeated measurements while Type B uncertainties are evaluated by other means apart from statistical methods. Every quantitative measurement result has two fundamental components, which are a numerical value that is expressed in SI units, as required by ISO 15189, and a measure of standard or combined uncertainty.

1.4.1 Type A standard uncertainty

Consider *Xi* to be an input quantity which is estimated for *n* independent observations. If the sample mean of *xi* is for *Xi*, *k* observations calculated then standard uncertainty *u*(*xi*) is expressed as:

$$u(x_i) = s(\bar{X}_i) = \left(\frac{1}{n(n-1)} \sum_{k=1}^{n} (X_{i,k} - \bar{X})^2 \right)^{1/2}$$

……………. (1)

Where *u*(*xi*) = uncertainty in measurement and s = standard deviation

1.4.2 Type B standard uncertainty

[7] states that this uncertainty is based on all of the relevant information available on the possible variability of *Xi*. This information may include

- Previous measurement data
- A good understanding of the properties of the materials and instruments
- Manufacturer's specifications
- Data provided in calibration and other certificates
- Uncertainties from reference data.

Other sources of uncertainty in measurement could be;

- Effects of variation in environmental conditions on the measurement which can be caused by factors such as temperature and humidity.
- Individual bias in reading analogue instruments.
- Finite instrument resolution or discrimination threshold.
- Standards and reference materials.
- Inexact values of constants and other parameters used.
- Approximations and assumptions.
- Variations in observations of the measurand.

1.5 Errors in measurement

Errors in measurement could come from the process used in carrying out the measurement, the instrument itself, the part, the operator's skills, the environment in which the measurement is carried out and the nature of the measurement whether it is manual or automatic. Errors in measurement are basically of two types: random and systematic.

Systematic errors (or offsets) are the constant values by which a measurement instrument's readings are off from the true or reference value (or a master value). Whereas, random errors are measurement errors caused by differences among operators, differences among the measuring equipment, differences over time, or differences due to changes in the environmental conditions [2].

Errors can be categorized broadly using 5Ms used in the manufacturing industry [8] as shown below and captured in Fig 1.

- Machine (technology) error is a geometric error associated specifically with the built or the construct of the measuring device.
- Method (process) errors have to do with measurement systems and procedures or guidelines in doing measurements.
- Materials (Includes Raw Materials, Consumables and Information) are affected by temperature variations called thermal effects. These errors occur when the measuring equipment or measured part expands or contracts due to temperature variations.
- Man Power (physical work) error; as the name implies is an error made by the operator or human being doing a measurement.
- Measurement (Inspection) error refers to procedures or guidelines for doing inspections.

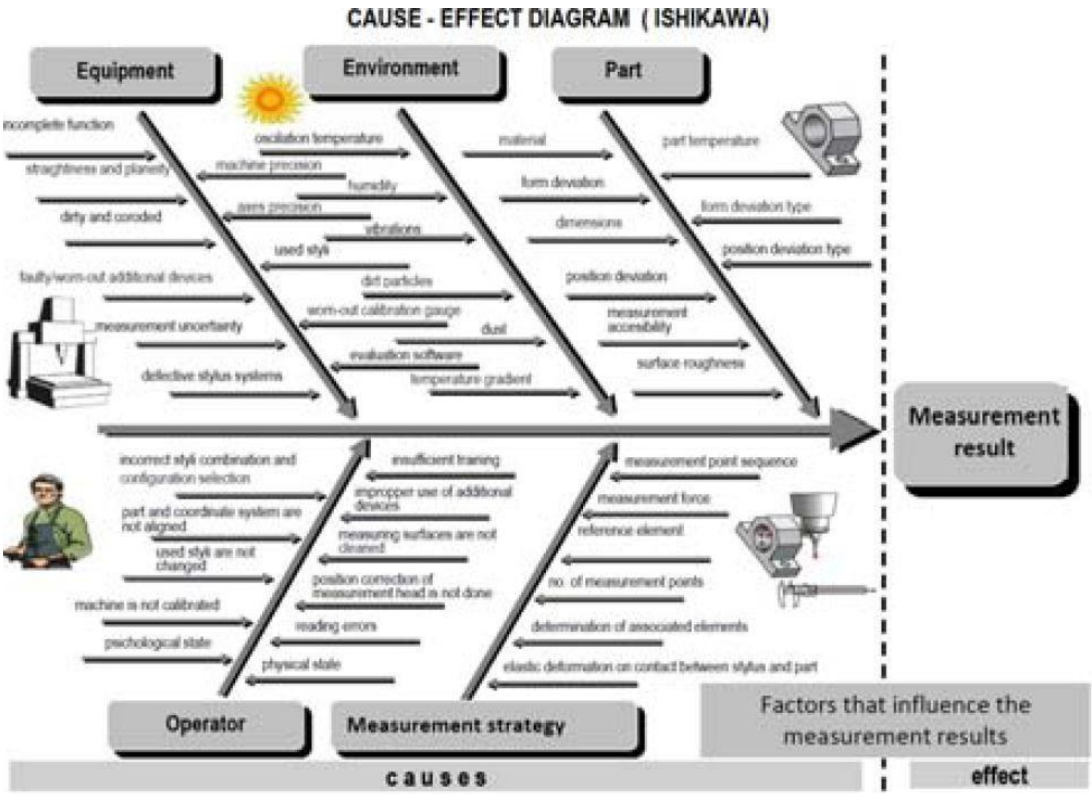

Figure 1: Cause – Effect (Ishikawa) diagram [8]

2.0 GR & R Review

Measurement systems in metrology can either be manual, partially automated or fully automated. Automated systems are becoming more attractive because they are more reliable and eliminate human error but manual set-ups are seen almost everywhere. But with all the innovation and modernization, is automated metrology more accurate, precise and reliable in terms of repeatability and reproducibility than manual metrology? The question here is what this paper seeks to attempt to answer. This paper aims to study, analyse and review GR & R measurement systems. Furthermore, a critical survey of literature relevant to gauging R&R systems in determining variation in manual and automatic measurement systems would be undertaken and an effective literature review. The review compares the various options available in performance measurement systems.

2.1 Al-Refaie & Bata Procedure

[9] proposed a procedure for assessing a manufacturing process and the capabilities of the measurement system using GR&R experiments which were designed with four quality measures; precision to-tolerance ratio, signal-to-noise ratio, discrimination ratio and process capability index and then using analysis of variance (ANOVA) to estimate variance components [9]. An assessment of the capability of a measurement is dependent on the proper quality measures. [9] used the variability in the product, σ^2_p and gauge variability, σ^2_g to total variance to be:

$$\sigma^2_{total} = \sigma^2_p + \sigma^2_g \quad \text{……………………. (2)}$$

It was stated that gauge variability, σ^2_g has two components: one for repeatability, $\sigma^2_{repeatability}$ and the other for reproducibility, $\sigma^2_{repeatability}$ and their relationship is as shown below.

$$\sigma^2_p = \sigma^2_{reproducibility} + \sigma^2_{repeatability} \quad \text{…….. (3)}$$

The same procedure estimates the capability of the quality measure in assessing the ability of the measurement system and that of the manufacturing process.

This procedure however good, seems to have failed in objectively considering the other GR & R models. Perhaps, that would have confirmed or further disproved the accuracy or usability of these models. Moreover, this is still a proposal not yet proven in the industry.

2.2 Pan's Comparison of GR&R Models

[10] compared the analysis of the accuracy of GR&R studies among three methods: ANOVA, Classical GR&R, and Long Form. These studies are performed per the standard, QS9000 to evaluate the suitability of a gauge [10]. It is said that [11] used the analysis of variance (ANOVA) to find the total variation

of measurement while the Classical method was proposed by [12]. Long Form the third method introduced by [13] is used to estimate the total variation of measurement of GR&R and the value of precision to tolerance.

In ANOVA the measurement process variability according to [10] can be defined as:

$$\sigma^2_{gauge} = \sigma^2_{repeatability} + \sigma^2_{reproducibility} \quad \text{...... (4)}$$

Where σ^2_{gauge} is the variability of the measurement process, therefore

$$\sigma^2_{total} = \sigma^2_{part} + \sigma^2_{gauge} \quad \text{......... (5)}$$

And σ^2_{part} is the product variation. Tsai's (1989) stipulated that ANOVA is a two-factor model governed by Eq. 6.

$yijl = \mu + Pi + Oj + POij + Rijl$ ……….………… (6)

Where

- i, j and l are vectors and
- μ: measurement mean
- Pi: effect of the product
- Oj: effect of inspector.
- (PO)ij: effect of interaction between product and inspector.
- Rij l: Effect of replicate measurements (error term

The condition to use Classical GR&R to estimate repeatability and reproducibility is that all Rj fall within the control limits of the R chart for ensuring stability to assess the measurement system. LongForm on the other hand, uses the sample range method to estimate repeatability and reproducibility. He concludes by saying that ANOVA is the most accurate.

In this comparison, much was said about ANOVA and how other important quantities can be related. That is good but on the other hand, very little was said about the other methods. This does not show a critical comparison as it sticks with one method.

2.3 Vardeman & VanValkenburg's Model

[14] figured out a two-way random-effects model for gauge R & R studies to criticize current practice and point out some ways of improvement from this given model. In the given model, where the two-way random-effects in Eq. 7 is given by;

$y_{ijk} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \varepsilon_{ijk}$ …………………… (7)

Variance, σ^2 is a measure of the repeatability variation whereas the sum of variance components is

$$\sigma^2_{reproducibility} = \sigma^2_{\beta} + \sigma^2_{\alpha\beta} \quad \text{................ (8)}$$

This indicates that the R & R study is dependent on the parameters α and β which they refer to as normal and μ is an unknown constant. The main objective here is to estimate σ and $\sigma_{reproducibility}$ which is used in the analysis of variance (ANOVA) for the point-based estimation model. It begins with calculating the quantities investigated using R & R studies to obtain the variants.

After using several point-based estimation methods for the analysis, the paper failed to point out clearly what will required for improvement. Furthermore, most of the comments and remarks from this work come as general comments or remarks and no specifics.

2.4 The FR-R measure by Payne, J., & Cariapa, V

FR-R known as a fixture repeatability and reproducibility is proposed by [15] to evaluate the performance of machining fixtures. This method is closely related to GR & R but uses machine fixtures. It considers two types of fixtures actually: the first is the machining fixture and the second is the gauge fixture. This is used to evaluate the degree of variability as stated by [15] that one segment of the variation consists of the variance on the part when it is located and clamped under static conditions. The second phase of variation is generated under the dynamic conditions that occur when the part is machined. It fundamentally quantifies the variability a fixture can contribute to the overall variance.

Fixture repeatability and reproducibility is given by:

$$FR - R = \sqrt{(EV)^2 + (AV)^2} \quad \text{.................... (9)}$$

The variance is given by;

$$\sigma_{FR-R} = \frac{FR - R}{5.15} = \sqrt{\sigma^2_E + \sigma^2_A} \quad \text{.............. (10)}$$

Where:

- EV or E = Equipment Variation AV
- or A = Appraiser Variation
- σ = Variability

The proposers of this measure (FR&R) were kind enough to acknowledge its limitations. The measure is limited in use to parts that cannot be easily manoeuvred and as a computer- based technique, it can be affected by modelling errors. It can take some time and it's not cheap.

2.5 Smith, McCrary & Callahan's GR&R studies

[16] conducted research which focused on the theory –practice gap which they said appeared to exist between the actual use of measurements by manufacturing professionals and the theories of gauge control in measurements. They concluded that GR&R is not used as often as it should in practice. This issue results in much emphasis being placed on instrument calibration and not the measuring abilities of the inspectors involved.

Several corrective measures were proposed but to what extent these measures are accepted or taken into consideration cannot be ascertained. Also, the feasibility and workability of these measures need to be confirmed.

2.6 Gauge Analysis Capability by Antony, Knowles & Roberts

[17] illustrated that there exists a fundamental difference between Classical Gauge Capability Analysis (CGCA) and Analysis of Variance (ANOVA). These represent the two of the GR&R methods mentioned earlier in section 2.2. Two examples were carried out; one for each method and data analysis was done. It was concluded that CGCA takes into account only the operator contributions and gauging equipment variability while ANOVA utilizes this factor and also includes the interaction between the operator and part. This is the greatest undoing of CGCA [17].

This study might have shown the insufficiency of the CGCA over ANOVA but this is not verified for most situations and all times. It also raises some important issues like the suitability of a method and perhaps if ANOVA has any downsides at all.

2.7 Assessment of GR&R robustness

[18] demonstrated differences between two prominent GR&R examination methods: the average and range (X and R) and two-way analysis of variance (two-way ANOVA). According to [18], the X and R method breaks the overall variation into three categories. The two-way ANOVA method further considers the appraiser-by-part interaction as shown in Table 1.

Table 1: Summary of X and R, two-way ANOVA methods' comparison [18]

Case study	$\overline{X}$ and R method acceptable results	Two way ANOVA method		Robust method for Gauge R&R analysis
		Acceptable results	Residual distribution of two way ANOVA	
Case 1 further	Yes	No	Non normal	$\overline{X}$ and R method
Case 2	Yes	Yes	Non normal	$\overline{X}$ and R method
Case 3	Yes	Yes	Non normal	$\overline{X}$ and R method
Case 1 initial	No	No	Normal	Both methods (two way ANOVA method preferred
Cast 4 inner	Yes	Yes	Normal	Both methods (two way ANOVA method preferred)
Case 4 outer	Yes	Yes	Normal	Both methods (two way ANOVA method preferred)

2.8 GR&R with/in another procedure

GR&R studies can be used with or in other procedures for performance evaluation as shown by [19] in the paper titled "Improving Wooden Parts' Quality by Adopting six-sigma define- measure-analyse-improve-control (DMAIC) Procedure". A crossed GR&R design where certain parts are measured many times by several operators was utilized. Two quality measures were adopted to assess the system. These where precision-to-tolerance (P/T) ratio:

$$P/T\ ratio = 6\sigma_{gage} / USL - LSL \quad \text{..........................} (11)$$

And the signal-to-noise (SNR) ratio:

$$SNR = \sqrt{2\sigma^2_{product} / \sigma^2_{gage}} \quad \text{..................} (12)$$

USL and LSL are the upper and lower specification limits and other symbols have their usual meanings in Eq. 11 and Eq. 12.

$$\sigma^2_{gage} = \sigma^2_{repeatability} + \sigma^2_{reproducibility} \quad \ldots (13)$$

and

$$\sigma^2_{total} = \sigma^2_{product} + \sigma^2_{gage} \quad \text{................} (14)$$

2.9 Renishaw Equator 300 gauging system - SP25/MODUS

Renishaw Equator a new gauging system as claimed by [20] is capable of high-speed comparative gauging for inspection of high-volume manufactured parts. The company boast that this piece of innovation can be installed within minutes, it's easy to operate and easy to program and it has good thermal stability. Renishaw went on to say that the Equator is faster and repeatable and it incorporates an integrated stylus changing of SM25 modules and CMM probes.

The Equator controller as reported by [20] is a dedicated control system that provides a suitable environment for running the system software. This versatility adds to its ability to be integrated into automated cells using interface cards. Any CMM programming software can be installed within the Equator software.

[21] states that an entire Equator system includes a port stylus changing rack, SP25 probe system, controller, one fixture plate and stop button or joystick kit—all at the running cost of $26,000.

A good number of things have been said about this product by the manufacturer but a comprehensive review of the end users will be needed to confirm this. Furthermore, it is a new product whose durability can only be proved with time. Renishaw's evaluation of the Equator is good but again, how many small companies can afford it?

2.0 GR & R Review

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2.10 Dimensional metrology interoperability

Zhao, *et al.*, [22] brought to the fore an important issue associated with dimensional metrology; the challenge of interoperability in dimensional metrology. This concept is defined by [23] as the ability of two system components to communicate correctly and completely with each other with minimal cost to either the component user or component vendor.

Interoperability deals directly with software and interfaces that interconnect dimensional metrology components. The dimensional measuring system will be most effective if the software applications are seamlessly integrated at the information interfaces.

Furthermore, [24] divided dimensional metrology into four parts: product definition, measurement process planning, measurement process execution, and analysis and reporting of quality data. Fig 2 depicts the relationship between these parts.

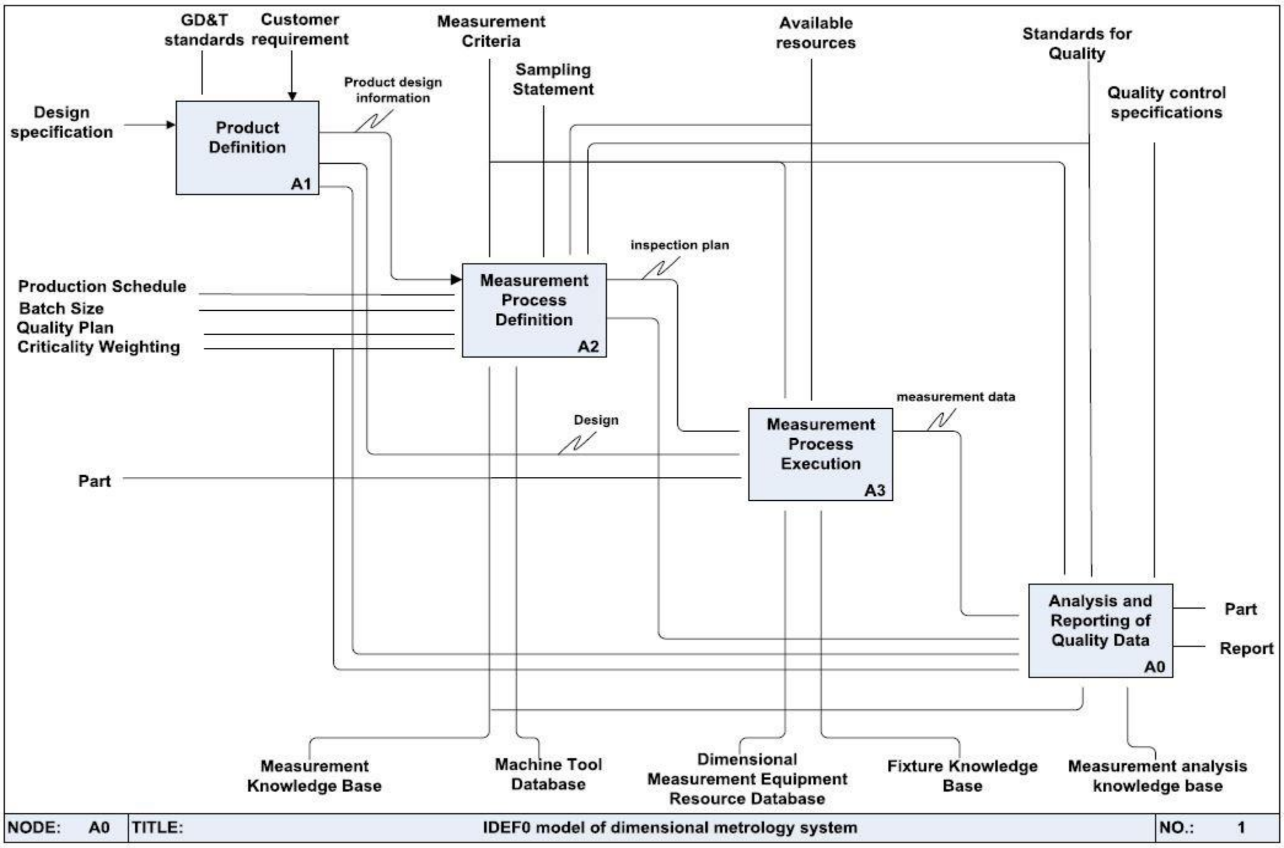

Figure 2: IDEFO model of dimensional metrology system [24]

This paper explored interoperability considerably and proposed a new data model to correct the gaps. However, how this issue impacts directly or indirectly on every dimensional metrology aspect including GR & R studies and to what extent remains a subject for further studies. Also, the proposed new data model is built on another relatively new solution which may require a new understanding. This compounds the issue.

2.11 Measurement Uncertainty by Meyer

[25] quoted GUM's definition of measurement uncertainty as the parameter associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurement. The paper also looked at the top-down and bottom-up approaches for resolving measurement uncertainty. The top-down approach obtains a measurement uncertainty from reproducibility whereas the bottom-up approach calculates the uncertainty by the addition of variances in Eq. 14:

$$uc\,(M) = \mathrm{M}\sqrt{\left(\frac{\mathrm{u(a)}}{a}\right)^2 + \left(\frac{\mathrm{u(b)}}{b}\right)^2 + \left(\frac{\mathrm{u(c)}}{c}\right)^2 + \left(\frac{\mathrm{u(d)}}{d}\right)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (15)$$

Where M is the measurand, a, b, c and d are factors for calculating M, u(x) is the standard uncertainty of factor x and uc (M) is the combined uncertainty.

Tools for determining measurement uncertainty as discussed here include standard deviations, flow diagram and Ishikawa diagram, equation of the measurand, other standard uncertainties, calculation rules, Monte Carlo method and expanded uncertainty. Uncertainty sources abound everywhere. Some basic sources described here were: volumetric operations, weighing, purity of standards and reference materials, atomic and molecular weights, multiple- point calibration (linear regression) and recovery. All of these sources are prone to large numbers of parameters. This shows how important it is to deal with uncertainties in metrology.

2.12 Measurement Analysis by Sahay

In [2], it stated that conclusions which are drawn from results that are obtained from statistical methods depend so much on the accuracy of data collected. For instance, if a measurement procedure and the measuring instrument are incapable of making repeatable and accurate measurements then, the results would be significantly impaired with measurement errors. This measurement error can be projected using accuracy and precision.

A measurement system analysis is therefore devised to assess the variance components and determine how much of the variation is due to the measurements. This system of analysis is mostly referred to as Gauge R&R Study. As usual total variation is dependent on the variation by part and gauge as shown in the Eq. 16, Eq. 17 and Eq. 18.

Note: All symbols have the same as mentioned earlier.

$$\sigma^2_{total} = \sigma^2_{part} + \sigma^2_{gauge} \quad \ldots\ldots\ldots\ldots\ldots\ldots (16)$$

$$\sigma^2_{measurement\ error} = \sigma^2_{gauge} = \sigma^2_{repeatability} + \sigma^2_{reproducibility} \quad \ldots\ldots\ldots\ldots\ldots\ldots (17)$$

$$\%R\&R = \frac{\sigma^2_{measurement\ error}}{\sigma^2_{total}} \times 100\% \quad \ldots\ldots\ldots\ldots\ldots\ldots (18)$$

[2] went further to suggest methods of gauge analysis as shown in the Fig 3 below.

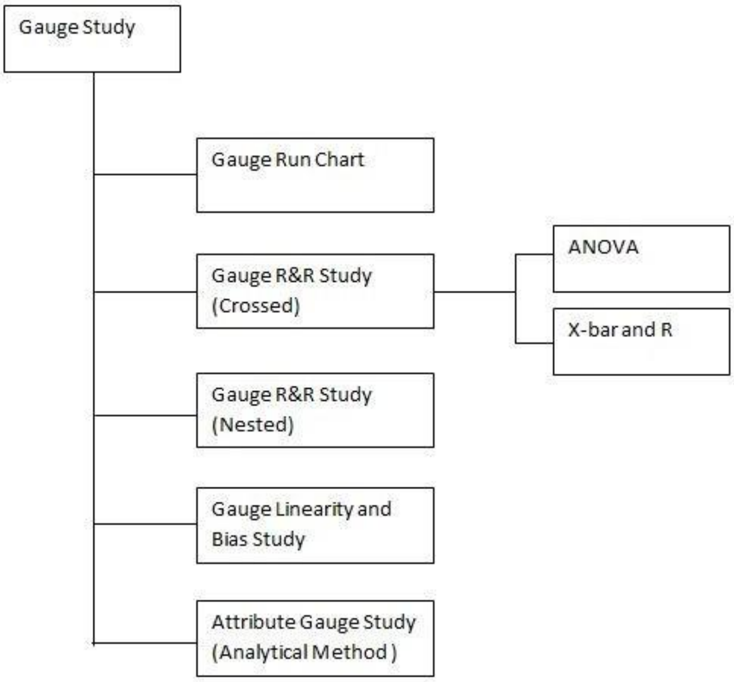

Figure 3: Methods of Gauge R&R Analysis

3.0 CONCLUSION

In It has been deduced from the reviews that various factors such as environment, measurement strategy, measurement uncertainty, operator contributions, gauging equipment, interaction between operator and part, interoperability of machine components such as software and hardware and the accuracy of data obtained can affect GR & R studies at varying degrees. Some of the methods for GR & R analysis encountered include ANOVA, Classical GR & R, LongTerm, two-way random effect model, fixture R & R, Average and Range and two-way ANOVA. Most of the GR & R studies and analyses under review here centered around these methods. One of the striking things discovered is that the ANOVA method or its variations seem to have a better grip and more dynamic for GR & R studies.

Quality measures used for evaluating the above methods were precision-to-tolerance, signal-to-noise, discrimination ratio and process capability index. These measures can be improved upon to get a method that is broad and covers more GR & R study scenarios while it is desirous to find out which GR & R method is best for which case.

It is also observed that more and more researchers are pointing towards combining methods to produce a single strategy for GR & R studies and analysis superior to any single method.

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