The GRR a Fundamental Tool for Dealing with Measurement System Variability

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With increasing complexity of machinery and products manufacturing the strict requirements for quality and, reliability of the measurement equipment and systems plays significant role in production system and quality assurance in terms of customer satisfaction. In nowadays automotive industry in connection to ISO/TS 16949:2009 there has been observed a strong confrontation with request for proof of suitability for use of selected gauges for a specific operations. An appropriate methodology allowing to determine a gauge the most suitable for a given operation is Gauge Reproducibility and Repeatability study (GRR or R&R). The GRR takes into a consideration the variability of produced parts, operator`s approach, and whole measurement system. The article deals with a description and the adequate methodology, and the experimental implementation of GRR in manufacturing quality process assurance in order to set up and continuously improve the quality level in automotive parts production.

Keywords: quality assurance, measurement variability, GRR, R&R, MSA

1 Introduction

Due to a complexity of contemporary manufactured products the whole product quality is not merely one simple characteristic but it is composed out of many particular characteristics materialized in product. In different words it is literally a set of characteristics with different level of importance. The quality of final product generally originates from a couple of stages and follows the quality spiral (market survey; conception, research and development; project and design; manufacturing planning; supply & suppliers; tools, jigs and device; manufacturing; process management; final control; sale; service; market survey, and so on.) Each activity assumes a particular quality level achievement, each segment must be linked to previous one, and incorrectly performed operation in the weakest link can jeopardize the total effort for reaching the required quality level [1]. From the project management point of view and product life stages there has been defined four significant stages for product quality assurance thus far. These are the product and process design and development, pre-serial stage of production, serial production, and service operation stage. In connection to pre-serial stage of production the APQP (Advanced Product Quality Planning) methodology and PPAP (Production Part Approval Process) are used in order to guarantee customer satisfaction during preparation process and the serial production afterwards. The APQP is organized into five stages (see figure 1).

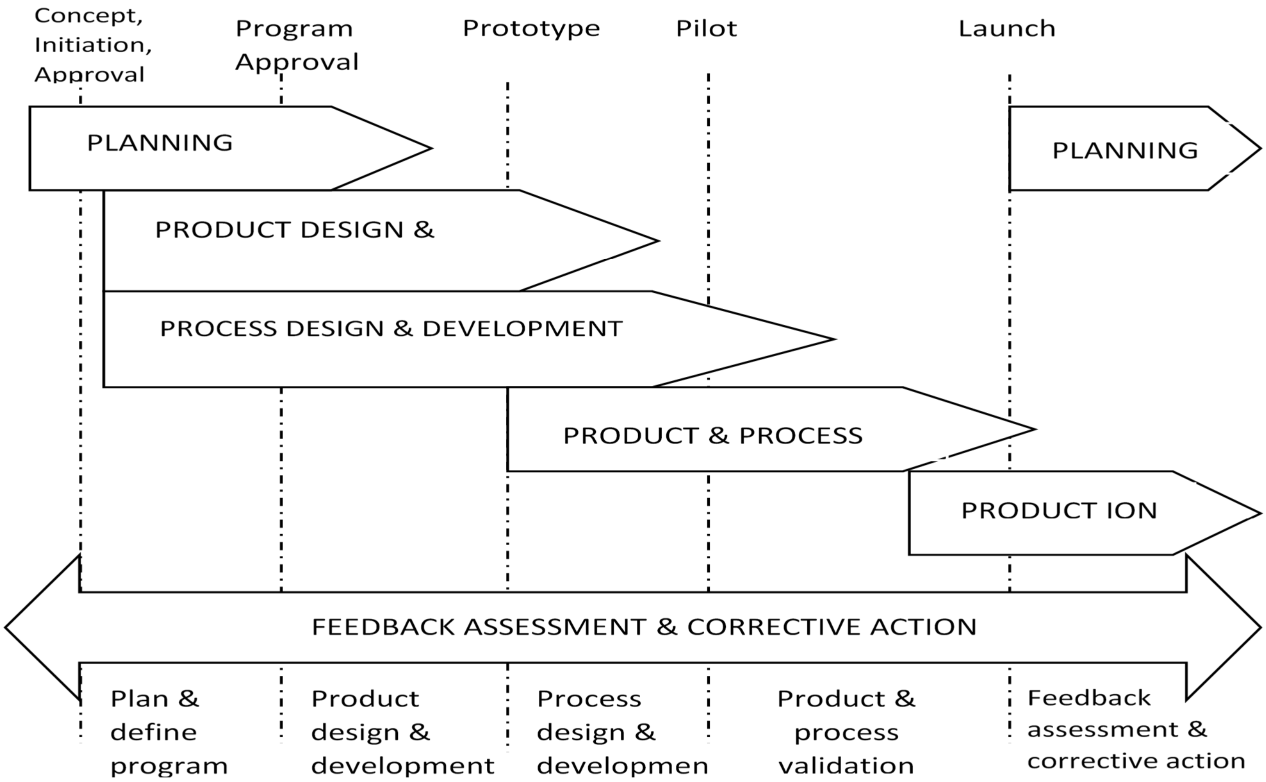

***Fig. 1** The APQP Process [2]*

One of the required outputs from APQP process, particularly in "Product and process validation stage" is the evidence of measurement system appropriateness. This analysis is necessary to be performed in order to control characteristics identified in control plan based on technical specification. Furthermore, specified monitoring, measurement equipment, and methods should be used. Such an equipment and methods must be regularly checked especially during manufacturing validation phase or just beforehand. For this reason a well-known and used methodology within an automotive industry is „Measurement System Analysis" where in its scope there has been elaborated the Gauge Reproducibility and Repeatability approach (GRR, GR&R, R&R) [3] as a very useful tool being able to provide relevant data in order to perform qualified decision. On the other hand the fundamental requirement for the evaluation of measurement equipment is anchored in ISO/TS 16949:2009 [4] and ISO 9001:2016 as well.

2 The Variability in Measurement System

Describing the process of variability in measurement system the one can start with term of observed variability which is the variability of measured value that is observable on gauge display. The observed variability results from a mutual influence of factors as measured characteristic, sensor, measured method, signal quality etc. The main variability sources can be determined firstly as "Real variability of measured characteristics", and secondly as a "Real variability in measurement system" then [5]. In the system of controls during manufacturing process is the finding of particular value of product characteristics and its comparison to customer specifications the crucial ability. The characteristic`s variability depends upon its stability in time, geometrical and material features, interaction with an operator and the gauge itself. The variability itself reveals two fundamentals unknowns. It is the variability of measurement system from metrology reason or variability of measured characteristics from the necessity to know the real value of the measured characteristics. The variability of measured characteristics is connected to production or manufacturing process and its natural sources of variability. These sources can be depicted as 6M (Man, Material/Part, Gauge/Device, Method, Etalon, and Milieu). Based on the MSA approach there can be used the method SWIPE (Standard, Workpiece, Instrument, Person/Procedure, and Environment) or PISMOEA (Part, Instrument, Standard, Method, Operator, Environment, Predisposition) .The process variability must be less than permissible tolerance of characteristics described by designer [5]. The measurement system is composed of interconnected factors like operator, measurement equipment (gauge, device, and instrument), measurement procedure, measurement characteristics, and finally the milieu. Each measurement equipment is further described by its own metrological characteristics. In order to precisely catch the variability, two approaches has been used so far, particularly the gauge capability and gauge reproducibility and repeatability.

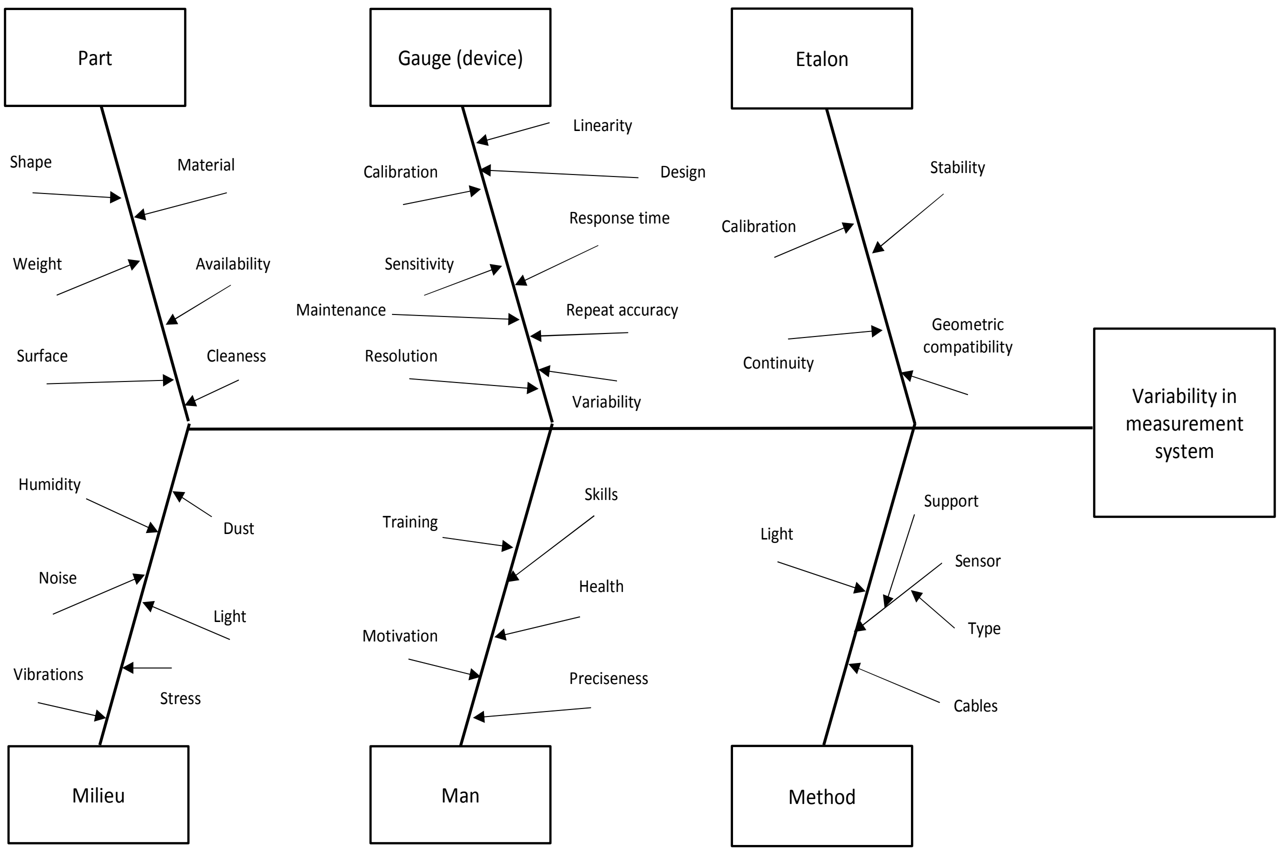

Fig. 2 The Cause and effect diagram of variability in measurement system [2, 5]. The figure is considered as universal model for variability sources elaboration

2.1 Gauge Reproducibility and Repeatability methodology (GRR, GR&R, R&R)

The accuracy of the measurement device is defined in CSN 010115:1996 standard as its ability to provide output signal close to true value. Actually the accuracy is more complex and significant problem. The influence of repeatability and particular operators` contribution must not be neglected. The influence of these flaws on the measurement the method described as R&R copes with. Performing R&R analysis it is necessary to take in account the total nature variability that includes repeatability, reproducibility, variability of parts, and mostly the variability of one part, or the variability from allowed tolerance range. In the first case when natural variability of process fills the greater range of tolerance better results are obtained while the latest one when natural variability of process fills lesser range of tolerance [6]. The evaluation of measurement system is performed on real manufactured parts. The manufactured products plays a role of standards in this case. The real values of standards are not necessary to be find out because of having no influence on result. The method itself consists repeated measurement of one particular dimension performed on a couple of different parts of the same manufactured product by a few operators. Each operator performing measurement repeats the measurement a couple of times. The final evaluation of equipment is provided in a form of %R&R including equipment variability (repeatability), and appraiser variability (reproducibility) as percentage of total variation. The measurement process is acceptable when results for operators are repeatable and results between operators are reproducible. The equipment is able to detect the variability between the manufactured parts whenever the variability of operator`s measurement is small owing to process variability. The percentage of process variability attributable to measurement system (%R&R) is determined once the measurement process is appropriate and detects the variability of part from the other [6]. With mathematical expression we consider %R&R as following [6]:

$$\sigma_m = \sqrt{\sigma_e^2 + \sigma_o^2} \tag{1}$$

σ_m…Measurement system standard deviation
σ_e…Equipment (instrument) standard deviation
σo...Operator (appraisal) standard deviation

Measurement system analysis declares standard deviation of manufactured parts as the element of total variability R&R of equipment.

$$\boldsymbol{\sigma_T^2 = \sigma_P^2 + \sigma_m^2} \tag{2}$$

σ_T…Total variability
σ_P…Part standard deviation

The percentage of variability of the measurement system corresponding to measurement system for repeatability and reproducibility (%R&R) is determined by formula:

$$\%R\&R = \frac{\sigma_m}{\sigma_T} \cdot 100 \tag{3}$$

The percentage of tolerance having relation to measurement system for repeatability and reproducibility is calculated with formula:

$$\%\,tolerance = \frac{5.15\,\sigma_m}{USL-LSL} \cdot 100 \tag{4}$$

Tolerance = USL – LSL
USL…Upper Specification Limit
LSL…Lower Specification Limit
The final step of numerical analysis is to determine a number of different categories that can be reliably distinguished by measurement system. It concerns a number of non-overlapping 97% confidence intervals covering the range of expected product variability.

$$ndc = \frac{\sigma_P}{\sigma_m} \cdot 1.41 \tag{5}$$

Ndc…Number of Distinct Categories

The general approach mentioned above can be substitute with the most common nomenclature in contemporary automotive industry using following expressions:

$$EV = \bar{\bar{R}} \cdot K_1 \tag{6}$$

EV…Equipment variability (Repeatability)
$\bar{\bar{R}}$…Average range
K_1… "Coefficient of one trial". $K_1 = 5.15/d_2$; d_2 is dependent on the number of trials (m) and number of parts times the number of operators (g) which is assumed to be greater than 15 [7].

$$AV = \sqrt{\left(\overline{X_{Diff}} \cdot K_2\right)^2 - \frac{(EV)^2}{n \cdot r}} \tag{7}$$

AV…Appraiser Variability (Reproducibility)
$\overline{X_{Diff}}$…Maximum difference of operator`s averages
K_2…"Coefficient of number of operators". $K_2 = 5.15/d_2^*$; d_2^* is the dependent on the number of appraisals (m), and (g) is 1, since there is only one range calculation. The coefficient K_2 for three operators equals 2.70 [7].
n…Number of parts
r…Number of operators

$$R\&R = \sqrt{(EV)^2 + (AV)^2} \tag{8}$$

R&R…Repeatability and Reproducibility

$$PV = \overline{R_p} \cdot K_3 \tag{9}$$

PV…Parts Variation
$\overline{R_p}$…Parts Range Averages
K_3…"Coefficient of number of parts". $K_2 = 5.15/d_2^*$; d_2^* is the dependent on the number of parts (m), and (g) is 1, since there is only one range calculation. The coefficient K_3 for ten parts equals 1.62.

$$TV = \sqrt{(R\&R)^2 + (PV)^2} \tag{10}$$

TV…Total Variation

For an analysis considering the tolerance range instead on process variability we use in denominator TV= (USL-LSL)/6

$$\%EV = \frac{EV}{TV} \cdot 100 \quad (11)$$

$$\%\boldsymbol{AV} = \frac{\boldsymbol{AV}}{\boldsymbol{TV}} \cdot \mathbf{100} \quad (12)$$

$$\%\,\boldsymbol{PV} = \frac{\boldsymbol{PV}}{\boldsymbol{TV}} \cdot \mathbf{100} \quad (13)$$

$$\%\boldsymbol{R}\&\boldsymbol{R} = \frac{\boldsymbol{R\&R}}{\boldsymbol{TV}} \cdot \mathbf{100} \quad (14)$$

Tab. 1 *Guidelines for Gauge R&R acceptance [5, 6, 7].*

%R&R < 10%	The measurement system is acceptable
10% < %R&R < 30%	May be acceptable, based upon the importance of application, cost of the gauge, cost of repair etc.
%R&R > 30%	Measurement system is unacceptable, and needs improvement

Finally the number of distinguished categories which should supposed to be greater than 5.

$$\text{ndc}=1.41 \cdot \frac{\text{PV}}{\text{R\&R}} \quad (15)$$

The GRR principle stems from a selection of ten manufactured parts when the measurement is performed and provided by three operators. Each chosen manufactured part is marked by a unique number in order to follow precise sequence of measurement avoiding the parts interchange. Incidental interchange would lead to violation of accurate repeatability. By number marked parts play the role of etalons (standards). With one identical instrument (device) each operator measures a particular dimension on ten parts totally three times while the operator switches after finishing the series of ten parts. The identical measurement is performed for each selected dimension. The obtained data are evaluated based on particular mathematical equations especially with formula of repeatability (equipment variability), the formula of reproducibility (appraisal variability), and finally with R&R equation. The obtained data are recorded to check lists or data sheets. The data sheets enables to carry out the calculation and display all the required results. The required output is in a form of %R&R or %GR&R. Finally the report is supplemented with X-R chart [6, 7, 8].

2.2 Material and Methods

In real conditions of technical practice we are often facing a question whether we can consider the obtained data as relevant and accurately measured or not and whether they describe real process or is there any significant shift of values due to measurement system. The R&R study enables to determine how big the observed variability is originating from the process due to variability of the measurement system. The proposal of the device evaluation was based on demand of Mitutoyo Czech Republic s.r.o. in Teplice. The main goal of the requirement was to determine suitability of several measurement device for measurement of particular manufactured part. For the evaluation a digital caliper of series 500 (device error ± 0,2 mm), micrometer of series 293-148 (device error ± 2μm), ultra-precise micrometer of series 293-100 (device error ± 0,5μm), and height gauge had been chosen from a series of touch devices. Moreover, a laser scanning micrometer of series 544 as untouched device was used as well. The analyzed part was hanging bolt used in automotive industry considered as safety part.

Fig. 3 *Hanging bolt M6 x 13*

The selected cutting from drawing on figure 2 reveals the highlighted dimensions where the measurements were undergone. The particular dimensions were defined by customer and are listed below.

1. Total part length
2. Thread length
3. Thread heel diameter
4. Thread diameter

An expected result of performed measurement applied on hanging bolt is to determine the lowest possible variability of the measurement system and then choose the most appropriate device for a particular dimension, and to propose the most suitable device for each selected dimension, afterwards. The proposal of the best suitable device for each selected dimension is based on evaluation using %R&R index. The previously mentioned index verifies whether the obtained results from the performed measurement are relevant for managerial decisions and it is consequently merely focused on device itself. The experiment procedure is listed in following bullets:

- The numerical marking of ten parts plays the role of etalons at the moment. Breach of the numeric sequence can lead to depreciation of results of %R&R index. The parts` numbering must be assured for all the measurement with all device as well as the operators.
- The operators performed three measurements on ten manufactured parts after choosing a first di-

mension shown on drawing (see the figure 4) using a first device the digital caliper in this case.

- The three remaining dimensions were also measured up with the digital caliper.
- The identical procedure was performed using micrometer, ultra-precise micrometer series 293, height gauge, and laser scanning micrometer series 544.

All the measured dimensions and results obtained were recorded into data sheet and the %R&R index calculated. The calculated results are depicted in table 2.

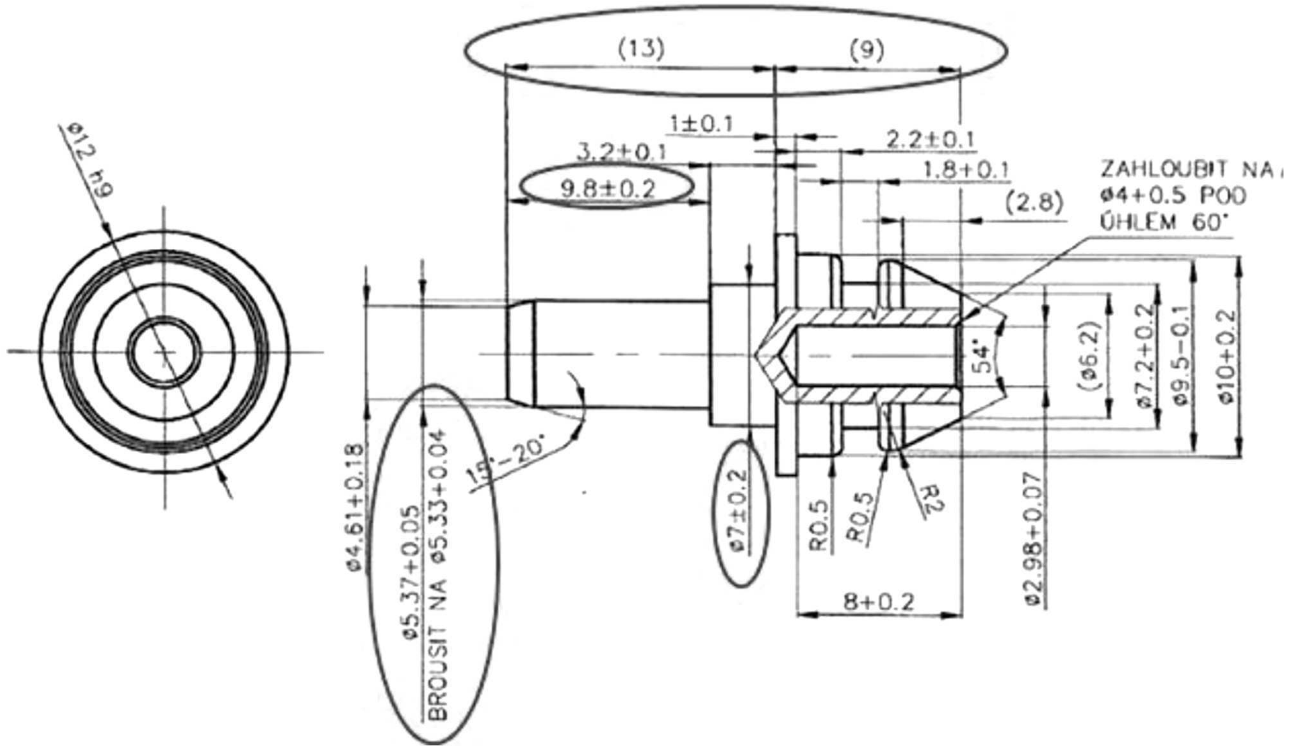

Fig. 4 *Selected cutting from production drawing*

Tab. 2 *The calculated %R&R index based on performed measurement [9]*

Device type	Measured parameters and calculated %R&R			
	Total part length	Thread heel diameter	Thread length	Thread diameter
Caliper	18.19	13.82	21.38	-
Micrometer	6.95	10.47	-	9.03
Ultra-precise micrometer	6.66	2.02	-	11.82
Height gauge	-	-	13.24	-
Laser scanning micrometer	20.85	5.45	-	5.89

The results obtained:

1. Total part length – the most suitable device based on the %R&R evaluation is the ultra-precise micrometer with reached result of 6,66 % of measurement system process variability.
2. Thread heel diameter - the most suitable device based on the %R&R evaluation is the ultra-precise micrometer with reached result of 2,02 % of measurement system process variability
3. Thread length - the most suitable device based on the %R&R evaluation is height gauge with reached result of 13,24 % of measurement system process variability
4. Thread diameter - the most suitable device based on the %R&R evaluation is the laser scanning micrometer with reached result of 5, 89 % of measurement system process variability.

3 Conclusion

The article deals with the fundamental necessity of quality assurance approach focused particularly on methodology of evaluation the variability of measurement system process. There has been a methodology of repeatability and reproducibility discussed, describing the formulas important for a real application the GRR methodology in manufacturing enterprises. Furthermore, the role of this methodology has been shown in context of the most common approach in automotive area the APQP process. The main objective of this experiment had been focused on R&R methodology especially to determination and utilization of the most suitable particular measurement instruments/device/equipment for a control of selected key parameters of hanging bolt for the automotive industry. During the experiment a number of measurement was performed using three operators and a number of selected device particularly the digital caliper, ultra-precise digital micrometer, height gauge and further laser scanning micrometer. In real manufacturing processes it usual that each measurement is influenced by an error. There has been defined a plethora of unfavorable factors influencing the measurement device or instrument and the whole measurement system, particularly the temperature, vibrations, humidity, air drift, jigs design, gauge design, parts surfaces, device ergonomics etc. One of the crucial factors influencing the measurement is the human factor represented by the operator who performs the measurement. One of the possibilities how to determine the suitability of measurement device for a particular dimension is R&R study. In connection to the realized experiment the R&R study reveals the suitability of selected device for a particular selected dimensions of hanging bolt. Based on the previously mentioned for the measurement of the total length the ultra-precise digital micrometer is recommended with %R&R index of 6.66% of variability of measurement system process. For the dimension of thread heel diameter the digital micrometer can be recommended due to the calculated value of %R&R index of 2, 02 % of variability of measurement system process. Furthermore, for the dimension of thread length the recommended device is the height gauge with the calculated value of %R&R equals 13, 24 % of variability of measurement system process. Finally, the best measurement of thread diameter can be performed using the laser scanning micrometer with value of %R&R equals 5.89% of variability of measurement system process. The experiment demonstrated the pertinence of GR&R (R&R) study as the general methodology in terms of determination of the best suitable instrument/device/gauge for dimensions measurement particularly applied for hanging bolt in this article. The article can be considered as a general instruction methodology either in terms of theoretical or practical approach when assessing variability during measurement in order to determine all the consequences in decision making process.

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