Recenzované výzkumné články

Present Approaches to the Analysis of Repeatability and Reproducibility of the Measurement Systems

Súčasné prístupy k analýze opakovateľnosti a reprodukovateľnosti systémov merania

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The paper presents basics of measurement system analysis (MSA) that plays an important role in helping organizations to improve their product quality. The aim of the paper is to map the current situation of this field, on which the attention has been focused on during the recent years and, on the contrary, on which the attention should be focused on for the future. The first part gives an insight into the MSA terminology and measurement system properties. Other parts describe the methods used by the GRR analysis, and then, analyse and compare each other. The A&R and ANOVA methods recommended by the AIAG manual are analysed, compared with the approach of evaluating the measurement process (EMP III) by D. J. Wheeler. Furthermore, areas that require further development are introduced. Specifically, these are non-replicable and multivariate measurement systems. In these cases, it is necessary to proceed in a different way since these measurement systems are affected by a number of other factors. As a conclusion, the work introduces the suitability of using the presented methods in different situations and outlines the areas that deserve further development.

Key words: *quality; measurement system; repeatability; reproducibility*

Článok predstavuje základy analýzy systému merania (MSA), ktorej významnou úlohou je zlepšovanie kvality výrobkov v organizáciách, a jej súčasné, prípadne budúce využitie. Nízka kvalita dát vedie k malému, resp. žiadnemu prínosu. Naopak vysoko kvalitné dáta môžu mať veľký prínos pre celkový proces či finálneho zákazníka. Aby sa zaistil dostatočný prínos získaný z použitia nameraných dát, a znížili sa tak náklady na jeho dosiahnutie, je treba sa zamerať práve na kvalitu týchto dát. Kvalitu nameraných dát je možné vyhodnotiť na základe násobných meraní získaných zo systémov meraní, ktoré pracujú za stabilných podmienok. Jedným z najbežnejších dôvodov vzniku dát nízkej kvality je ich príliš veľká variabilita. Účelom MSA je teda určiť rozsah pozorovanej variability spôsobenej systémom merania a identifikovať zdroje premenlivosti v tomto systéme. Najbežnejšou štúdiou v MSA na vyhodnotenie štatistických zmien v procese merania je analýza opakovateľnosti a reprodukovateľnosti (GRR analýza). Cieľom práce je zmapovať aktuálne dianie v tejto oblasti, a naopak, kde by mohla byť sústredená pozornosť do budúcna. Prvá časť poskytuje prehľad o terminológii MSA a vlastnostiach systému merania. Ďalšie časti popisujú metódy, ktoré GRR analýza používa, a následne sú analyzované a porovnané. Analyzované sú metódy priemeru a rozpätia (A&R) a analýza rozptylu (ANOVA) odporúčané príručkou AIAG, a porovnané sú s prístupom hodnotenia procesu merania (EMP III) podľa D. J. Wheelera. Výsledkom je rada rozdielov, ktoré prístup EMP III ponúka, ako napr. nové hodnotiace kritérium ICC (triedny koeficient korelácie), metriky počítané na základe rozptylu, kategorizácia systému merania do štyroch tried, útlm signálov zmien procesu, ktoré sú degradované chybou merania. Záver práce predstaví vhodnosť využitia predstavených metód v rôznych situáciách. Ďalej na základe zmapovania súčasného diania MSA sú načrtnuté oblasti, ktoré si zaslúžia ďalší vývoj. Konkrétne sa jedná o systémy nereplikovateľných meraní alebo systémy merania viacrozmerných premenných, kde je nutné postupovať iným spôsobom, nakoľko tieto systémy merania ovplyvňuje rada ďalších faktorov. V súvislosti s systémom nereplikovateľných meraní sa jedná o deštrukciu alebo porušenie skúšaného dielu vplyvom skúšky, čo vedie k použitiu ďalších prístupov. S vyvíjajúcou sa výrobnou technológiou a systémov merania viacrozmerných premenných sa výrobky stávajú stále sofistikovanejšími s viac ako jednou kvalitatívnou vlastnosťou. A teda, s využitím klasického postupu GRR analýzy a zvyšujúcim sa počtom premenných merania môže dôjsť ku skresleniu hodnôt. Preto je nevyhnutné vykonávať viacrozmernú GRR analýzu pre systémy merania s viacrozmernými premennými. Vyššie spomenuté metódy a ich modifikácie môžu byť výzvou pre budúci výskum.

Klíčová slova: *kvalita; systém merania; opakovateľnosť; reprodukovateľnosť*

Nowadays manufacturing companies gather an extensive amount of information through measurement and inspection. On the basis of these data they make important decisions about product quality and process control. Logically, it is very important to know what is the quality of the measured data. Answers to this question are provided by analyses of the measurement system. For the companies, which are suppliers of automotive industry, the processing of these analyses is one of the requirements of the quality management system defined in standard IATF 16949 [1].

The measurement system is a collection of instruments or gages, standards, operations, methods, fixtures, software, personnel, environment and assumptions used to quantify a unit of measure or fix an assessment to the feature characteristic being measured [2]. The Measurement System Analysis (MSA) can be defined as an experimental and statistical method for determining the amount of variations that exist within a measurement process. The following data should be reviewed: the measurement data being collected, the methods and tools used to collect and record the data [3]. The four issues regarding the measurement system are important [4]:

– readability including the smallest readable unit, measurement resolution, scale limit, or detection limit,
– effective resolution which is the sensitivity of a measurement system when process variation for a particular application,
– reference value which is the accepted value of an artifact and it requires an operational definition used as the surrogate for the true value,
– true value which is an unknown and untraceable actual value of an artifact.

Variation in the measurement process can contribute to the overall process variability. Reliable data can prevent wasted time, labour and scrap in a manufacturing process. An ineffective measurement system can allow acceptation of bad parts and rejection of good parts, resulting in dissatisfied customers and excessive scrap.

1. Properties of the measurement system

Knowledge of measurement systems properties is very important in assessing the conformity of products. The conformity or nonconformity of a product can be clearly confirmed only if the entire interval of measurement uncertainty lies within or outside the tolerance. If the uncertainty interval includes a tolerance limit, the compliance test result is inconclusive [5]. Let us suppose that we would use four different products with values near the lower limits of tolerance to make a set of repeated measurements and we would present the distribution of the measured values using the Gaussian curve (Fig. 1).

The individual situations should be interpreted as follows:

– situation A: nonconformity with the requirements is guaranteed
– situations B and C: the result of the conformity test is inconclusive
– situation D: conformity with the requirements is guaranteed.

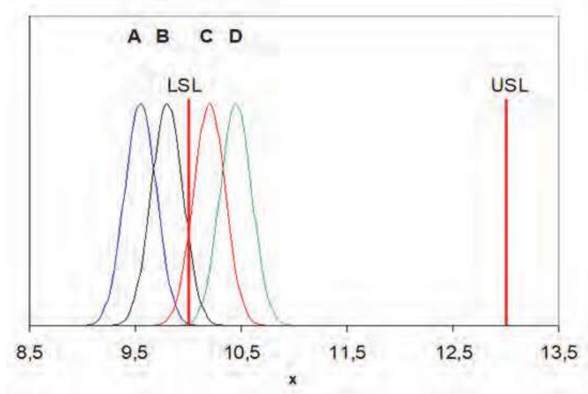

Fig. 1 Various situations of distribution of the repeated measurements of the monitored characteristic [6]

Obr. 1 Rôzne prípady rozdelenia opakovaných meraní sledovaného znaku [6]

The figure clearly shows that the increased variability of the measurement system significantly narrows the interval of values, in which the product conformity with the requirements is guaranteed. In an extreme case, where the variability of measurements is higher than width of the tolerance, the conformity with the requirements would not be guaranteed for any product.

The properties of measurement can be divided in principle to location variation, width variation and system variation including capability, performance and uncertainty. The location variation includes bias, stability and linearity. Bias is equal to the difference between the observed average of measurements and the reference value. Stability (drift) is the change in bias over time. Linearity is the change in bias over the normal operating range. The width variation describes the properties such as precision, repeatability, reproducibility, GRR, sensitivity, consistency and uniformity. Precision is a proximity of repeated readings to each other or a random error component of the measurement system. Repeatability is a variation in the measurements obtained with one measuring device when used several times by an appraiser while measuring the identical characteristic on the same part, commonly referred to as Equipment Variation (EV). Reproducibility is a variation in the average of the measurements made by different appraisers using the same gage when measuring a characteristic on one part, commonly referred to as Appraiser Variation (AV). GRR means gage repeatability and reproducibility that is the combined estimate of the measurement system repeatability and reproducibility. Sensitivity is defined as the smallest input that results in a detectable output signal. Consistency is the degree of repeatability change over time. Uniformity means a change in repeatability over the normal operating range, in other words it is homogeneity of repeatability [2]. GRR analysis is the most common study in MSA used to evaluate the variations in the measurement process [7].

2. Methods of GRR analyses

Comprehensive GRR study can be performed by using one of the following techniques:

- A&R method (Average and Range method),
- ANOVA (Analysis of Variance),
- EMP III (Evaluating the Measurement Process).

Repeatability and reproducibility evaluation is performed on the basis of a measurement of a set of products representing the production range by different operators, or under various conditions corresponding to the practical application of the measurement system. The MSA methodology [2] describes A&R method and ANOVA method. They require that at least ten products must be measured and each operator measures each product sample at least twice. In order to obtain objective results, the measurements should be in random order and the study should include all operators who will perform the measurements.

The evaluation of repeatability and reproducibility of measurement system uses not only numerical calculations but also graphical tools. Range control chart is very important for verification whether the measurement process is in control in terms of the variability of repeated measurements. This verification should be performed at the beginning of the analysis and it may indicate the wrong approach of any of the operators or the excessive sensitivity of the measurement system. Also, the average control chart provides important information for comparison of measurements of individual operators and for evaluating the suitability of the measurement system in assessing variability of the product samples.

Numerical evaluation varies according to the method used. A&R method, the most commonly used in practice, estimates the repeatability on the basis of average range of repeated measurements of all samples by all operators and the reproducibility on the basis of the range of the averages of all measurements by the individual operators. Its main advantage is a clear process of evaluation, allowing processing in a spreadsheet, such as Excel. The ANOVA method already requires more complex calculations, and it is therefore mostly applied with use of suitable software. Its main advantage is the ability to identify another possible component of the measurement system variability, interactions between the operators and samples. Although these interactions are not very common in practice, they can significantly affect the results of the analysis [8].

The decisive criteria for assessing the acceptability of a measurement system are the percentage of repeatability and reproducibility from the total variation (%GRR) and the number of distinct categories (*ndc*) that are calculated according to the equations (1) and (2). The measurement system is judged to be entirely acceptable if the %GRR does not exceed 10 % and the *ndc* is at least 5.

$$\%GRR = \frac{GRR}{TV} \cdot 100 \qquad (1)$$

$$ndc = 1.41 \cdot \frac{PV}{GRR} \cdot 100 \qquad (2)$$

where GRR is combined repeatability and reproducibility of measurement system, TV is total variation and PV is part variation.

The information value of repeatability and reproducibility analyses of the measurement systems can be further improved. Other graphical analysis tools can be applied, for example to evaluate, whether the selected samples evenly cover the production range, to compare the measurements of each operator in detail, to detect any outliers or to evaluate some other properties of the measurement system. Better confidence of GRR analysis results can be achieved by increasing the number of the measured samples or trials. It was found that more significant narrowing of the %GRR confidence interval can be achieved by increasing the number of trials [9].

3. Evaluating the Measurement Process

Donald J. Wheeler, an expert in statistical process control, introduces a new approach of evaluating the measurement process (EMP) [10]. The procedure of the analysis is corresponding to the A&R method, but final evaluation of results is different. D. J. Wheeler and D. S. Ermer point out the statistical errors of the AIAG approach, the most significant of which is the use of ratios based on the standard deviation. Wheeler introduces a number of notable differences:

- metrics based on the variance σ^2 instead of the standard deviation,
- intra-class correlation coefficient (ICC),
- monitor classes which classify the measurement system into one of the four groups,
- probable error, which provides an absolute characterization of the measurement error,
- process signal attenuation, which estimates the percentage, by which the information provided by the process variation is degraded by the measurement variation.

A proper understanding of probable error and the intra-class correlation coefficient will allow us to quantify the uncertainty in the measurements and to know when the ability to use the measurements has been compromised [10]. D. J. Wheeler classifies the measurement system as the first, second, third or fourth class monitor based on the intra-class correlation coefficient. ICC is the ratio of the part variance $(PV)^2$ to the total variance $(TV)^2$:

$$ICC = \frac{(PV)^2}{(TV)^2} \qquad (3)$$

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The AIAG guideline [2] says about a measurement system acceptability that if variability of the measurement system is too high, it is an unacceptable measurement system and it must be rejected. However, D. J. Wheeler claims that an unacceptable measurement system (according to the AIAG conditions – Tab. 1) is still able to detect the points out of control. And this is the main purpose of the intra-class correlation coefficient value that indicates the relative usefulness of the measurement system. The EMP results are interpreted by four categories, which give an insight into the measurement system: firstly, how it can reduce the strength of a signal (point out of control) on a control chart, secondly, give the chance to the measurement system to detect a large shift, and thirdly, make it possible to track process improvements (see Tab. 1) [11, 12].

Tab.1 Characterization and comparison of evaluative criteria
Tab. 1 Charakteristika a porovnanie hodnotiacich kritérií

EMP III						**AIAG**	
ICC	**Type of class monitor**	**Attenuation of process signal**	**Chance of detecting ±3σ std. error shift**	**Ability to track process improvements**	**Classification**	**%GRR** (Corresponding ICC)	**Classification**
0.8 - 1.0	First class	Less than 10 %	More than 99 % with the rule 1	Up to Cp80	Acceptable	**0 to 10** (0.99 – 1)	Acceptable
						10 to 30 (0.91 – 0.99)	Conditionally acceptable
0.5 - 0.8	Second class	From 10 to 30 %	More than 88 % with the rule 1	Up to Cp50	Acceptable	**> 30** (< 0.91)	Unacceptable
0.2 - 0.5	Third class	From 30 to 55 %	More than 91 % with the rules 1, 2, 3, 4	Up toCp20	Acceptable		
0.0 - 0.2	Fourth class	More than 55 %	Rapidly vanishing	Unable to track	Unacceptable		

According to D. J. Wheeler the measurement systems belonging to the second or third class monitor can still be considered to be applicable, even though~~t~~, according to the AIAG approach it is decidedly unacceptable and must be rejected. Hence, EMP III is recommended to be used for detecting the process changes (to detect the out of control points in control chart and to indicate process improvement). It is very interesting, but it is applicable only for the cases when the measurement system is used for process monitoring. For the measurement systems, which are used for decision making about products conformity, the EMP III criteria cannot be applied.

4. Non-replicable measurement systems

Not all measurements can be replicated for each part. It is the case of destructive measurement systems or systems where the part changes during use/testing. Regarding the destructive measurement systems, when the measured part is destroyed by the act of measuring, the process is called destructive measurement. This includes for example destructive weld testing, destructive plating testing, salt spray/humidity booth testing, impact testing or mass spectroscopy and other processes for testing the material characteristic [4].

In the systems where the part changes during use/testing, there are also non-replicable systems where the part is not harmed by the measurement process, but the characteristic being measured will change, for example leak tests with qualitative data, testing using engine test stands, transmission test stands, vehicle dynamometers, etc. Analysis of these systems will depend on whether a homogeneous set of parts (small variation between parts) can be found to represent a single part; the shelf life of the characteristic is known and it extends beyond the expected duration of the study – i.e. whether the measured characteristic does not change over the expected period of use, and whether the dynamic properties can be stabilized.

The measurements of individual parts are not replicated so the study can be used with destructive and non-replicable measurement system. It assumes that the shelf life of the characteristic is known and that it extends beyond the expected duration of the study, the specimens cover the expected range of the process variation of the characteristic property and the measurement system linearity is documented over the expected range of the characteristic. Total variance is equal to the process variance and that of the measurement system. The following are several approaches that are used for conducting the non-replicable measurement system [13]:

- Split samples: The parts or material collected to represent one part are split or sub-divided into smaller units. The smaller units are used for the repeated trials and between operator trials.
- Consecutive samples: Consecutive parts are used to represent one part for the repeat trials and between operator trials. These are used when the parts cannot be sub-divided and consecutive parts can be reasonably expected to be homogeneous, such as it would occur in an auto-correlated process.
- Regression approach: The change in the characteristic over time or activity is known and has a defined relationship (e.g., shrinkage of plastic parts). The subsequent measurements are adjusted using this relationship and then analysed.
- Stabilized parts: Parts or systems are stabilized before measuring. This stabilization will depend on the product and characteristic. Some systems would be on some time disturbed (destabilized) compared to such systems that have been quite newly installed. Some characteristics may stabilize when pre-tested for a number of times.

The analysis of a non-replicable MSA is different. Some statistical software packages, such as Minitab, have an option for a Nested GRR devoted just to the non-replicable measurement systems. If this is not available, it is possible to use the Nested ANOVA option [13].

5. Multivariate measurement system analysis

Traditional MSA considers only a single quality characteristic. With the advent of modern technology, industrial products have become very sophisticated with more than one quality characteristic. Thus, it becomes necessary to perform multivariate GRR (MGRR) analysis for multivariate measurement system when collecting data with multiple responses [14]. If the data include correlated variables, analysts could be misled if they use univariate techniques. After all, the variables jointly affect the process. For instance, if analysts employ separate univariate control charts to track a multivariate situation, they will face a Type I error. The distortion of the values increases with the number of measurement variables [5].

When performing multivariate MSA for multivariate measurement systems, the optimal allocation of several parameters, such as the number of quality characteristics, sample size of parts, number of operators and replicated measurements, have not been considered in the multivariate GRR study either. As the total number of measurements increases, the estimated total variation becomes more precise, but the related inspection time and costs will be increased as well. Finding the right balance between the precision of the measurement system while still maintaining cost-effectiveness in determining the optimal allocation of parameters for correlated quality characteristics becomes an important issue in practical applications. The two parameters (number of samples and a total number of measurements) significantly affect the expected length of confidence interval. In order to determine whether the accuracy of a measurement system is adequate or not, we calculate it according to the equations in [15].

For conducting future MGRR study of the multivariate measurement system with three quality characteristics it is recommended, at first, to decide the gauges for measurement and the specifications of multiple quality characteristics; to determine the optimal allocation of the measurement parameters; to perform actual measurements and collect data for multivariate quality characteristics; to perform Mardia test to check the multivariate normality of the collected data and estimate the revised total variation of the measuring process by performing MANOVA (Multivariate Analysis of Variance); to evaluate the adequacy of multivariate measurement system based on the revised total variation. The precision of a multivariate measurement system is achieved with the required total number of measurements and its associated optimal allocation of parameters under three different scenarios [5].

Future researches may consider other numbers of multiple quality characteristics besides $v = 3$ and further extending the simulation and discussions from random-effect to mixed-effect MANOVA models in case that the number of operators is fixed. The other approval criteria, such as %GRR, number of distinct categories (*ndc*) need to be further explored when performing the MGRR analysis for correlated quality characteristics [16].

Conclusions

The aim of the article has been to highlight the importance of MSA and to analyse selected trends of current development in this field. It is important to perceive that the quality of the measured data is not determined only by usually calibrated measuring device itself, but also by the entire measurement system including a number of different factors. The suitability of the measurement systems is evaluated on the basis of a number of properties. Repeatability and reproducibility of the measurement system is being evaluated the most frequently. Current developments in the field of GRR analysis offer different approaches (A&R method, ANOVA, EMP and their modifications) and a number of possibilities to improve the evaluation objectivity. For some specific measurement systems, such as non-replicable or multivariate measurement systems, specific analytical procedures are developed. As a conclusion, the work introduces the suitability of using the presented methods in different situations and outlines the areas that deserve further development.

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25. výročí České koksárenské společnosti

V roce 1993 byla nadšenci v oboru koksárenství založena Česká koksárenská společnost, z.s. (ČKS). Svou činností navázala na působení bývalé koksárenské sekce ČSVTS. Dne 8. 6. 2018 ČKS oslavila svou 25letou existenci plenárním shromážděním členů. ČKS má dnes 150 individuálních členů, 14 členů – tuzemských právnických osob a 6 zahraničních členů – právnických osob. Pro své členy i ostatní zájemce provádí servis a pomáhá zajišťovat vzdělávání v oboru koksárenství formou seminářů a konferencí, zprostředkovává publikování nejnovějších poznatků a provozních zkušeností, pořádá zajímavé exkurze v domácích provozech i v zahraničí, a to nejen na koksovnách, ale i v závodech se souvisejícími a navazujícími obory.

Plenární shromáždění se uskutečnilo v reprezentačních prostorách kulturního domu Akord v Ostravě-Zábřehu. Mělo slavnostní i dělnou atmosféru. Pro další období si ČKS zvolila nové funkcionáře ve výkonné radě a revizní komisi, usnesla se na novém rozpočtu pro svou činnost a na rámcové, věcné náplni činnosti. Na plenárním shromáždění ČKS ocenila tři své zasloužilé pracovníky. Plenárního shromáždění se zúčastnili i zakládající členové, kteří stejně jako další účastníci diskuse přispěli řadou podnětných návrhů k činnosti společnosti. Pohled do jednacího sálu ukázal, že zájem o členství a činnost v ČKS stále trvá a že činnost ČKS vhodnou formou doplňuje odborné vyžití svých členů v jejich pracovním zařazení v závodech a organizacích, kde jsou zaměstnáni. To, že ze 150 individuálních členů je 40 členů již v důchodu, lze spatřovat jako pozitivní znak její činnosti. Z toho je totiž vidět, že ČKS jednak nezapomíná na pracovníky, kteří již odešli z pravidelného pracovního procesu, a dává jim možnost společenského uplatnění, jednak dovede využít jejich neocenitelné zkušenosti a znalosti získané dlouhodobou prací v oboru koksárenství.

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