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Analiza merilnih sistemov za zagotavljanje kakovosti v procesu šest sigm

Measuring-System Analysis for Quality Assurance in a Six-Sigma Process

Mirko Soković - Duško Pavletić - Romeo Matković

Danes na trgu avtomobilske industrije obstaja velika konkurenca zato morajo podjetja stalno izboljševati kakovost izdelkov/storitev če želijo obdržati svoj položaj. Zagotoviti je treba brezhibno delovanje poslovnega sistema ter nenehno izboljšanje vseh procesov v podjetju. Pri tem si pomagajo z različnimi metodami in orodji, tako že znanimi kakor tudi novejšimi, kakršna je metodologija Šest sigm - 6σ. V prispevku je razložena študija merilnih sistemov, ki so zelo pomemben element v metodologiji šest sigm.

(Ključne besede: sistemi merilni, variacije, metodologija šest sigm, študije ponovljivosti in primerljivosti)

To maintain market share, suppliers to the automotive industry must be involved in the continuous improvement of their processes. They have to strive to perfect their processes as well as their overall business. Therefore, the search for appropriate improvement methods is ongoing, whether these methods are well known or completely new, e.g., six-sigma (6σ) methods. This paper explains the analysis of measuring systems as a part of a six-sigma methodology.

(Keywords: measurement systems, variance, six sigma methodology, gauge repeatability and reproducibility (R&R) study)

0 UVOD

Dandanes je znano pravilo, da kupci postavljajo zahteve po 0 ppm slabih izdelkov, kar pomeni raven kakovosti 6σ. Takšne zahteve se postavljajo predvsem podjetjem, ki so zmožna zagotoviti raven kakovosti med 3σ in 4σ, in to tudi obvladovati ([1] do [3]). Pri ravni kakovosti 4σ je verjetnost dobave izdelkov ustrezne kakovosti okoli 99,9937 % ali 63 ppm. Teoretično se ta verjetnost lahko sprejme kot trenutno zadostna raven kakovosti, vendar če upoštevamo dopusten premik procesa za ± 1,5 σ (kar je v praksi najbolj pogosto), prihajamo do podatka, da je verjetnost pojave neustreznih izdelkov 99,379 % ali 6210 ppm. To dejstvo je, z vidika poslovanja podjetja in obstanka na zahtevnem avtomobilskem trgu, nesprejemljivo.

V celotnem sistemu uvajanja filozofije 6σ je pomemben element obvladovanje in analiza merilnih sistemov. Analiza merilnih sistemov se v osnovi omeji na statistične analize merilnih sistemov, ki se uporabljajo v izdelovalnem procesu. V metodologiji

0 INTRODUCTION

In the modern automotive industry, suppliers are expected to achieve a quality level as high as 0 ppm, which means a 6σ quality level. At present, many suppliers are capable of providing a quality level of 3σ to 4σ ([1] to [3]). At a 4σ quality level, the probability of delivering defective products is 0.000063 or 63 ppm. Such a level of quality is theoretically acceptable if we suppose that the process is without shifts. With shifts taken into account (based on experience, the process shifts that can usually be expected equal ± 1.5σ) the probability of delivering defective products is as high as 0.006210 or 6210 ppm. Such a level of delivered quality in the modern automotive industry is unacceptable.

An important element in 6σ methodology is measurement system analysis. Measurement system analysis deals with a statistical analysis of measurement systems used in production processes. In the context of 6σ methodology, measurement

6σ so znane bolj podrobne analize in statistične metode za obvladovanje merilne in preskusne opreme, to so: analiza ponovljivosti in primerljivosti (znana kot R&R), stabilnost, linearnost, razlikovanje itn. [4].

V prispevku bo prikazan vpliv merilnih sistemov na kakovost izdelkov ter celotno raven kakovosti. Če imamo ustrezen proces in ga želimo obvladovati na ravni procesa 6σ, ne bo ta nič boljši, če ga merimo z neustrezno merilno opremo ali merilno opremo, za katero ne vemo, kaj se z njo dogaja, oz. v kakšnem tehničnem stanju je. Merilni odstopek, ki iz tega izhaja, je zelo pomemben dejavnik pri merjenju, ker meritev z neustreznim merilom lahko zavaja in vodi k napačnem sklepu o samem procesu ali izdelku.

system analysis consists of the following: a detailed statistical analysis of a measurement and experimentation equipment or gauge R&R analysis, an analysis of stability, linearity and discrimination [4].

This paper deals with the effect of a measurement system on the quality of products and the overall quality of manufacturing. For processes that are at the 6σ quality level, the measurement equipment should also be at a high quality level; otherwise, the measurement error could be high, causing the wrong decision to be made.

1 ANALIZA MERILNIH SISTEMOV

Matematično analize merilnih sistemov vključujejo razumevanje variacij v procesu merjenja, kakor je prikazano v enačbi:

1 MEASUREMENT SYSTEM ANALYSIS

Measurement system analysis involves understanding measurement process variations, presented by the following equation:

$$\sigma_T^2 = \sigma_p^2 + \sigma_m^2$$

pri čemer pomenijo: σ_T^2 - skupna varianca, σ_p^2 - varianca procesa in σ_m^2 - varianca merjenja.

To je edini pravi način razumevanja variacij v procesu. Pri analizi merilnih sistemov se določajo statistične značilnosti: ponovljivost, primerljivost, linearnost, natančnost.

Ponovljivost določamo kot spremenljivost zaporednih meritev enega merilca, ki večkrat meri z istim merilnikom isto lastnost na istem merjencu. **Primerljivost** je mera za spremenljivost zaporednih meritev različnih merilcev, ki merijo isti merjenec ali iste lastnosti z istim merilnikom.

Linearnost je je mera zanesljivosti merilnika na celotnem merilnem območju merilnika.

Odmik je razlika med povprečjem izmerkov in imensko vrednostjo. Odmik predstavlja tudi mero točnosti.

Študija ponovljivosti in primerljivosti (PP) merilnih sistemov se uporablja tako za začetno oceno merilnih sistemov kakor tudi za določanje velikosti vpliva merilnega sistema na vrednost indeksa sposobnosti procesa.

where: σ_T^2 - total variance, σ_p^2 - process variance, σ_m^2 - measurement variance.

Measurement system analysis deals with several statistical characteristics: repeatability, reproducibility, linearity and bias.

Repeatability is a measure of the variability of successive measurements of the same part, or the same characteristic, by the same operator, using the same measuring instrument. And **reproducibility** is a measurement of the variability of successive measurements of the same part, or the same characteristic, by different operators, using the same measuring instrument.

Linearity is a measure of an instrument's accuracy over the range of the instrument's capability.

Bias is the difference between the average of the measurements and the nominal value.Bias also represents a measure of precision.

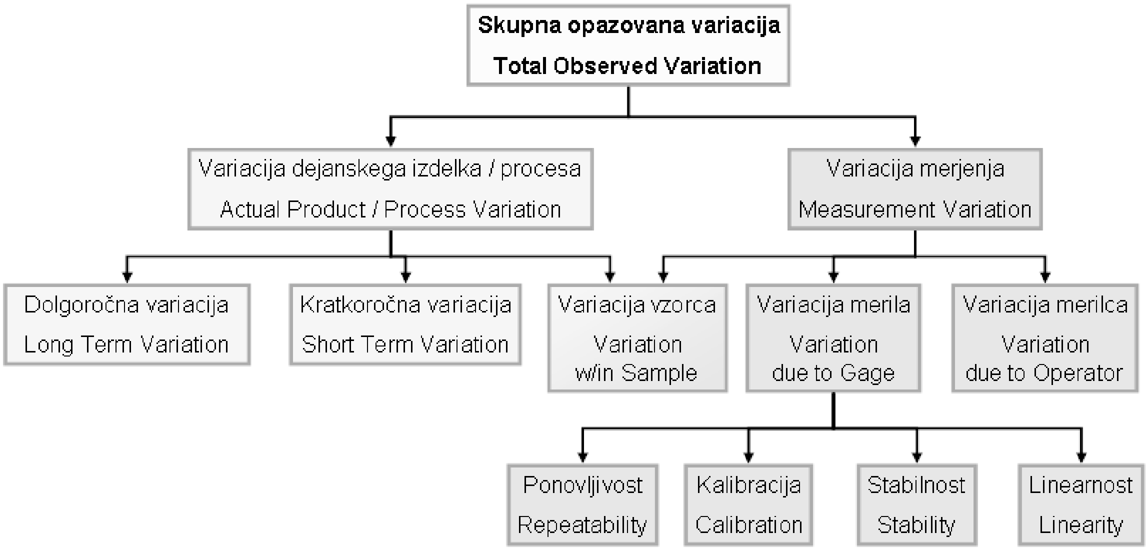
A gauge R&R analysis can be used for a first evaluation of measurement systems, as well as for finding the magnitude of a measurement system's effect on the process capability index.

1.1 Viri merilnih odklonov

Analiza merilnih sistemov izmeri in razpozna različne vire odklonov, ki lahko vplivajo na merilni sistem. Merilni odklon je skupna variacija

1.1 Sources of measurement variation

Measurement system analysis quantifies and identifies different sources of variation that might affect the measurement system. Measurement variation is the



Sl. 1. *Blokovni diagram skupne opazovane variance*
Fig. 1. *Total-observed-variation flow chart*

pri merjenju, ki je lahko posledica variacije na vzorcu merjenja ali variacije merilnega sistema. Na sliki 1 je nazorno prikazano, kako določimo skupno variacijo: ta je setavljena iz variacije meritve in variacije izdelka. Pomembna pri analizi merilnih sistemov je variacija meritve, ki izhaja iz variacije merilnega sistema (merilni instrument ali naprava, merilec, okolje itn.)

1.2 Vpliv merilnega odstopka na indeks sposobnosti procesa Cp

Merilni odstopek je prikazan na sliki 2 kot skupni seštevek odstopka izdelka in odstopka merilnega sistema. V prvem izrazu je definirana natančnost skozi srednjo vrednost meritve. V drugem izrazu izhaja natančnost kot mera variacije merilnega sistema.

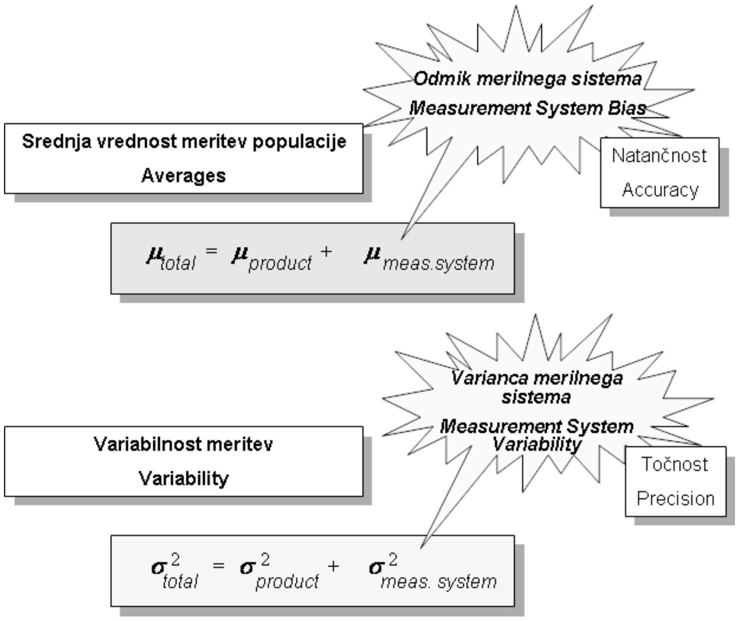
Na podlagi preizkusov in analiz proizvodnega procesa smo dobili rezultate, ki pokažejo, kako vpliva odstotek odmika merilnega sistema na indeks sposobnosti procesa Cp ([5] in [6]). S slike 3 je razvidno, da 10 % napake merilnega sistema skoraj ne vpliva na dejanski Cp izdelka. Izkaže se tudi, če pri izračunu sposobnosti za določen proces dobimo vrednost Cp = 1,3 in upoštevamo 10 % odmik merilnega sistema, bo tudi dejanski Cp približno enak. Vendar, ker je večja napaka merilnega sistema, je dejanski Cp boljši od opazovanega. To pove, da moramo zelo dobro poznati merilni sistem, preden

total observed variation in measurements, which can be attributed to the variation in the item being measured or to the measurement system itself. Components of the total observed variation are shown in Figure 1. The total observed variation includes the actual product/process variation and a measurement variation, which consists of the variation due to the operator, the variation due to the gauge and the variation within the sample.

1.2 Measurement error effect on the process capability index Cp

Measurement error as a result of actual product variation and measurement system variation is shown in Figure 2. The first equation defines the accuracy, taking into account the average of the measurements. The second equation defines precision as a measure of the measurement system.

A measurement error's effect on the process capability index Cp is determined through experiments and the process analysis, Figure 3. For example, 10% of the measurement system error has a negligible effect on the actual process capability index Cp ([5] and [6]). On the other hand, with an observed process capability index of Cp = 1.3 and a measurement system error equal to 10%, the value of the actual Cp will be approximately 1.3. If the measurement system error is bigger, the actual process capability is then better observed. This means that the measurement system error has to be



Sl. 2. *Skupna varianca in srednja vrednost*
Fig. 2. *Accuracy and precision of the measurement system*

ugotavljamo izhod določene meritve z ustrezno negotovostjo.

V primeru, ko smo analizo Cp delali z merilno napravo, ki ima odstotek merilnega odstopka do 30 %, je iz diagrama razvidno, da ta nima tako pomembnega vpliva na dejanski Cp. Vendar, če uporabljamo merilno napravo z več ko 30 odstotki merilnega odstopka, je zelo pomemben vpliv na dejanski Cp; pri 70 odstotkih merilnega odstopka je opazovani Cp = 1,3, dejanski pa Cp = 3,0.

Na podlagi tega bi lahko napačno sklepali, kaj se v resnici dogaja s procesom. Da bi se temu izognili, je treba vedeti, kaj se dogaja z merilnim instrumentom ter kako določiti odstotek merilnega odstopka, da bi lahko ustrezno ukrepali.

1.3 Kakovost merilnih sistemov

Merilni sistemi imajo določene karakteristike, po katerih jih razlikujemo glede na kakovost. Kakovost merilnih sistemov lahko delimo na:

- razlikovanje,
- natančnost, točnost, odmik,
- ponovljivost ali test-retest,
- učinek odmika vključno s primerljivostjo,
- stabilnost (skladnost),
- linearnost.

Vsaka od naštetih komponent merilnega odstopka vpliva na variacijo rezultatov meritev in

known in order to be certain of the measurements results.

In general, measurement system errors up to 30% will have little or no effect on the capability index, so the values of the observed and actual capability indices will be almost the same.
A measurement system error greater than 30% will have a significant effect on the capability index, e.g., with a measurement system error as high as 70% the observed process capability equals Cp = 1.3, while the actual Cp = 3.0.

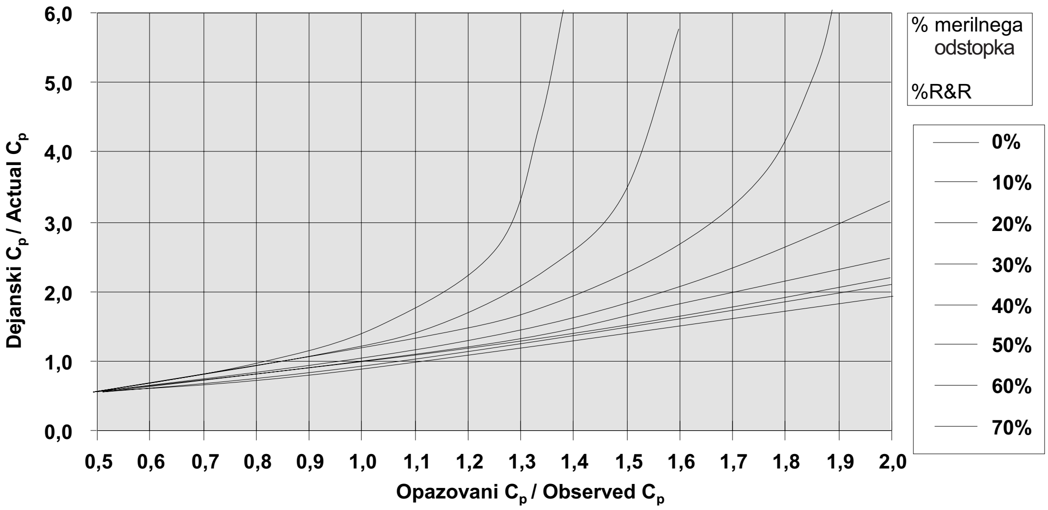
So, to make a sound decision about process capability, a measurement system should be evaluated and the magnitude of its variability should be taken into account.

1.3 Quality of measurement systems

Measurement systems have certain characteristics that define their level of quality. These characteristics are:

- discrimination,
- accuracy, precision,
- repeatability, or test-retest,
- bias effect with reproducibility,
- stability (consistency),
- linearity.

Each of the various components of measurement error can contribute to a variation in



Sl. 3. *Vpliv odstotka merilnega odstopka na indeks sposobnosti procesa Cp*
Fig. 3. *Measurement error effect on the process capability index Cp*

provzroča napačno sklepanje o kakovosti merjenca.

the given value causing the wrong decision to be made.

2 ŠTUDIJA PP ZA MERILNE SISTEME Z ODČITAVANJEM VREDNOSTI

Skozi predhodno razlago smo prišli do analize merilnih sistemov, ki podaja sklepno ugotovitev, kaj se dogaja z merilnim sistemom kot celoto, vključno z merilcem.

Merilni sistemi z odčitavanjem vrednosti so merilne naprave, ki imajo možnost merjenja z odčitavanjem določene mere (sl. 4) [7].

2 GAUGE R&R OF A MEASUREMENT SYSTEM FOR QUANTITATIVE DATA

So far we have a measurement system analysis that takes into account all the elements of a measurement system, including operators.

Measurement systems for quantitative data enable readings of a measured characteristic numerical value, Figure 4 [7].

Sl. 4. *Merilna naprava za merjenje višine*
Fig. 4. *Hight measurement gauge*

Pri šudiji posameznega merilnega sistema izhajamo iz naslednjih postavk [8]:
- merita dva ali trije merilci,
- običajno se meri 10 vzorcev,
- vsak vzorec se izmeri 2 ali 3 krat.

Študijo PP (ponovljivosti in primerljivosti) merilnega sistema uporabljamo, ko želimo ugotoviti ([6] in [9]):
- ali ima merilni sistem ustrezno razlikovanje;
- izvore variacij v merilnem sistemu;
- relativno velikost za vsak izvor variacije;
- ali je potrebno kakršnokoli ukrepanje, če je, kaj bi priporočili;
- kako bo skupina razumela ali bo merilni sistem ustrezen tudi v prihodnosti? Vključno s ponovljivostjo teh rezultatov v prihodnosti in potrebami raziskovanja.

Razume se, da smo v našo analizo vključili naslednje izvore variacij:
- meritev,
- vzorec nasproti vzorcu,
- merilec nasproti merilcu.

In general, gauge R&R is conducted in the following conditions [8]:
- the measurement is conducted by two or three operators,
- there are 10 units to measure,
- each unit is measured two or three times by each operator.

R&R analysis is used when the following are of special interest ([6] and [9]):
- Does the measurement system have adequate discrimination?
- What are the sources of variation in the measurement system?
- What is the relative magnitude of each of the sources of variation?
- Is there any action required, and what can be recommended?
- How will the team understand whether the measurement system will be adequate in the future, including the repeatability of these results in the future and developing needs?

The following sources of variation should be included in the analysis:
- measurement,
- part-to-part,
- operator-to-operator.

2.1 Postopek za izvajanje študije PP

1) Umeri merilo ali zagotovi, da je še umerjeno.
2) Zagotovi, da prvi merilec izvaja meritve skozi vse vzorce z naključnim izborom.
3) Zagotovi, da tudi drugi merilec izvaja meritve skozi vse vzorce z naključnim izborom.
4) Nadaljuj, dokler se ne zvrstijo vsi merilci, ki sodelujejo v raziskavi.
5) Ponavljaj korake 2 do 4 za vsa potrebna števila meritev.
6) Uporabi obrazec za ugotavljanje statističnih podatkov študij PP:
   a) ponovljivost,
   b) primerljivost,
   c) standardno odstopanje za obe prej omenjeni karakteristiki,
   d) odstotek PP,
   e) odstotek tolerančne analize,
7) Analiziraj rezultate in ukrepaj, če je potrebno.

2.1 Procedure for performing an R&R study

1) Calibrate the gauge, or ensure that it has already been calibrated.
2) Ensure that the first operator measures all the units once in a random order.
3) Ensure that the second operator measures all the units once in random order.
4) Continue until all the operators have measured all the units once.
5) Repeat steps from 2 to 4 for the required number of trials.
6) Use the form provided to determine the statistics of the R&R study:
   a) repeatability,
   b) reproducibility,
   c) standard deviation for each of the above,
   d) %R&R,
   e) % tolerance analysis.
7) Analyze the results and determine follow-up action, if any.

Število merilcev:
- Če so v postopku prisotni različni merilci oz. operaterji, izberi od 2 do 4 merilca z metodo naključne izbire.

Number of operators:
- If the process uses multiple operators, chose 2–4 at random.

- Če je v postopku samo en operater oz. merilec ali pa nobeden, opravi študijo brez učinka merilca (zanemari primerljivost).

Število vzorcev:
- Izberi zadostno število vzorcev, in to tako, da je: (število vzorcev) × (število merilcev) > 15.

2.2 Primer študije PP za merilni trn Marposs ϕ35,31 mm z metodo ANOVA

Poznani sta dve metodi analize PP, in sicer analiza PP po metodi ANOVA (analiza variance) ter po metodi $\overline{X}$ - R. Razlika med njimi je ta, da se metoda $\overline{X}$ - R več uporablja, ker kalkulacija izhaja iz kontrolnih kart in je bolj preprosta. Vendar je metoda ANOVA bolj natančna, ker:
- metoda ANOVA računa mogoče povezave med merilci in vzorci, metoda $\overline{X}$ - R pa ne;
- komponente variacije, uporabljene pri metodi ANOVA, so bolje ocenjene od razpona uporabljenega pri metodi $\overline{X}$ - R.

V nadaljevanju prispevka bomo podali primer študije PP, ki je bila narejena za proces izdelave okrova turbo kompresorja. Analizo smo naredili s programom MINITAB™, ki je prirejen za metodo ANOVA.

V proizvodnem procesu se za merjenje premerov okrova turbo kompresorja uporablja merilni trn Marposs, ki je sestavni del naprave Marposs E9066 in je prikazan na sliki 5. V danem primeru bo podana analiza PP za merjenje premera ϕ35,31 ± 0,08 mm (sl. 6) ([6] in [9]).

- If the process uses only one operator, or no operators, perform study without operator effects (ignore reproducibility effect).

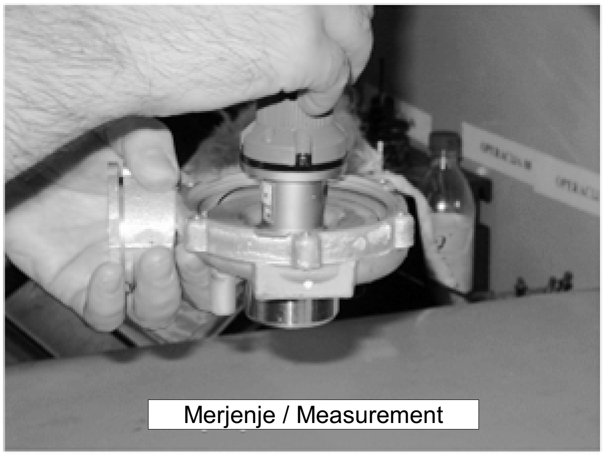
Number of samples:
- Select enough samples so that: (number of samples) × (number of operators) > 15.

2.2 Example of gauge R&R with ANOVA method for a Marposs ϕ35.31 mm measurement gauge

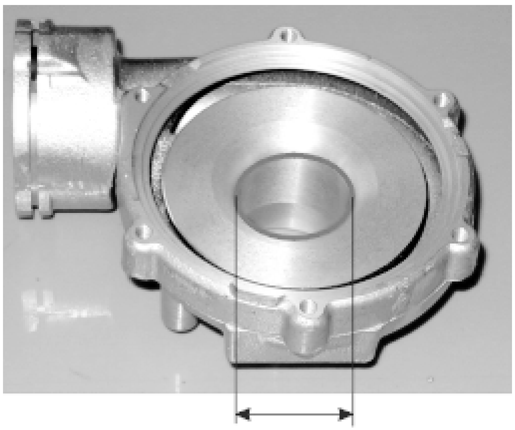
Two gauge R&R methods are known, the ANOVA and the $\overline{X}$ - R method. The $\overline{X}$ - R method is simpler and is used when the gauge R&R analysis is based on control charts. The ANOVA method is more precise because:
- The ANOVA calculates possible interactions between operators and samples, while the $\overline{X}$ - R method does not.
- Components of variation used by the ANOVA are better evaluated in comparison with the range used by the $\overline{X}$ - R method.

Later in the paper there will be an example of a gauge R&R analysis in the production of a turbo-charger housing. An analysis will be made with the ANOVA method using the MINITAB™ statistical analysis package.

The Marposs measurement gauge, which is part of the Marposs E9066 measurement system, is used to measure the diameter of the turbo-charger housing, Figure 5. In the presented example, a gauge R&R analysis for a ϕ35.31 ± 0.08 mm measurement will be shown (Fig. 6) ([6] and [9]).

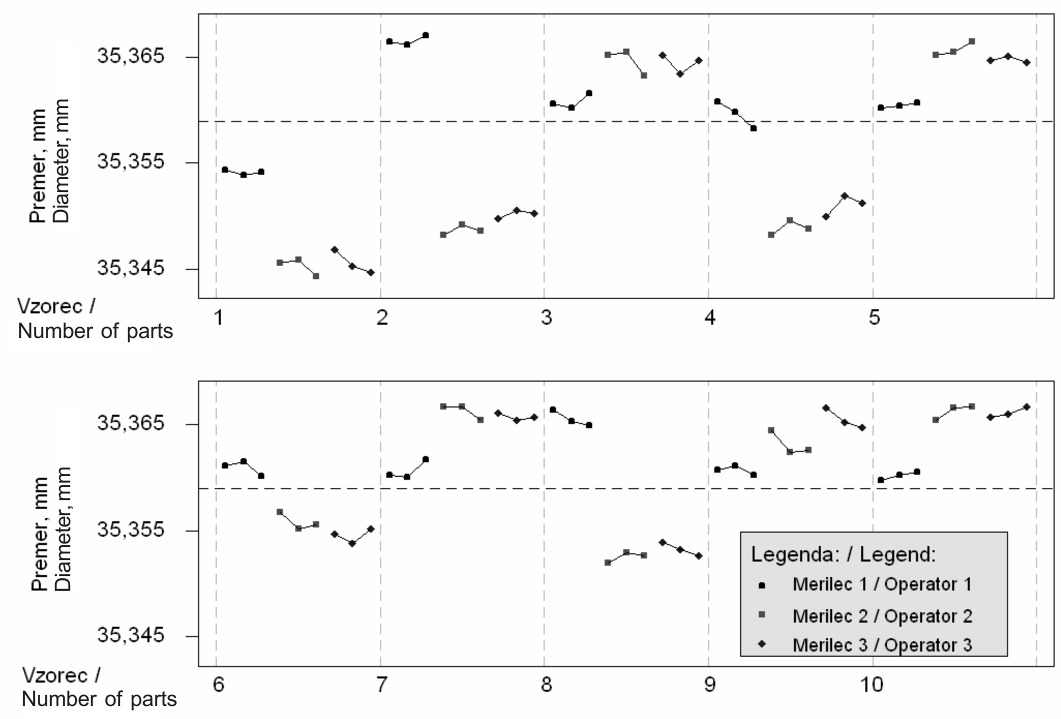


Sl. 5. *Merilna naprava Marposs in merjenje premera 35,31±0,08 mm*
Fig. 5. *Marposs measurement gauge and measurement of diamater 35.31 ± 0.08 mm*



ϕ35,31 ± 0,08

Sl. 6. *Pomembna kota na okrovu turbo kompresorja (tip 716108-2-20)*
Fig. 6. *Important dimension on the housing of turbocharger 716108-2-20*



Sl. 7. *Diagram poteka za meritve karakterističnega premera po merilcih in po vzorcih*
Fig. 7. *Flow chart of diameter measurement for operators and number of parts*

V analizi smo upoštevali vsa prej omenjena pravila. Na temelju dobljenih rezultatov smo naredili diagram poteka po merilcih in po vzorcih, kar prikazuje slika 7, ter kontrolno karto $\overline{X}$ - R za premer ϕ35,31 ± 0,08 okrova turbo kompresorja (sl. 8).

S slike 7 je razvidno, da je nekaj narobe z merilcem 1, ker se na nekaterih vzorcih meritev merilca 1 rezultati precej razlikujejo od preostalih.

S slike 8 je tudi razvidno, da se meritve merilca 1 razlikujejo od meritev drugih dveh merilcev. Na karti R je tudi razvidno, da je merilec 1 imel največji razpon pri meritvah in se njegove meritve ne ujemajo s preostalima dvema merilcema. To lahko pomeni, da merilec 1 ni zadostno usposobljen za izvajanje meritev.

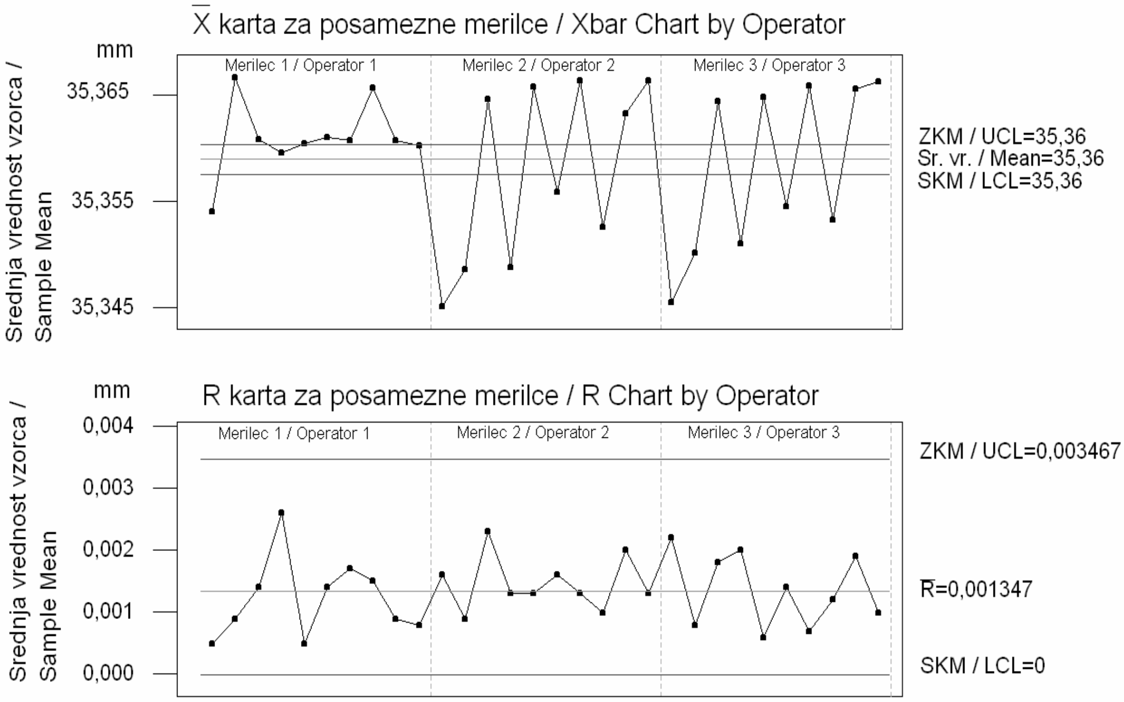
Na sliki 9 je podana celotna analiza PP v grafični obliki. Iz diagrama *Merilec*Vzorec medsebojno* je tudi razvidno, da merilec 1 ne ustreza; prav tem daje slabe rezultate ponovitve. Vendar ponovljivost meritev ni problematična, zato lahko sklepamo, da je treba bolj usposobiti merilca 1 za merjenje; po tem ponoviti meritve ter primerjati rezultate analize PP. Lahko že sedaj sklepamo, da bo merilna naprava ustrezna za merjenje, če se le bodo uskladili merilci.

In the example, the procedure for performing an R&R study is followed. Based on the measurements of the turbocharger-housing diameter 35.31±0.08 mm, a flow chart and an $\overline{X}$ - R control chart have been drawn, shown in Figure 7 and Figure 8, respectively.

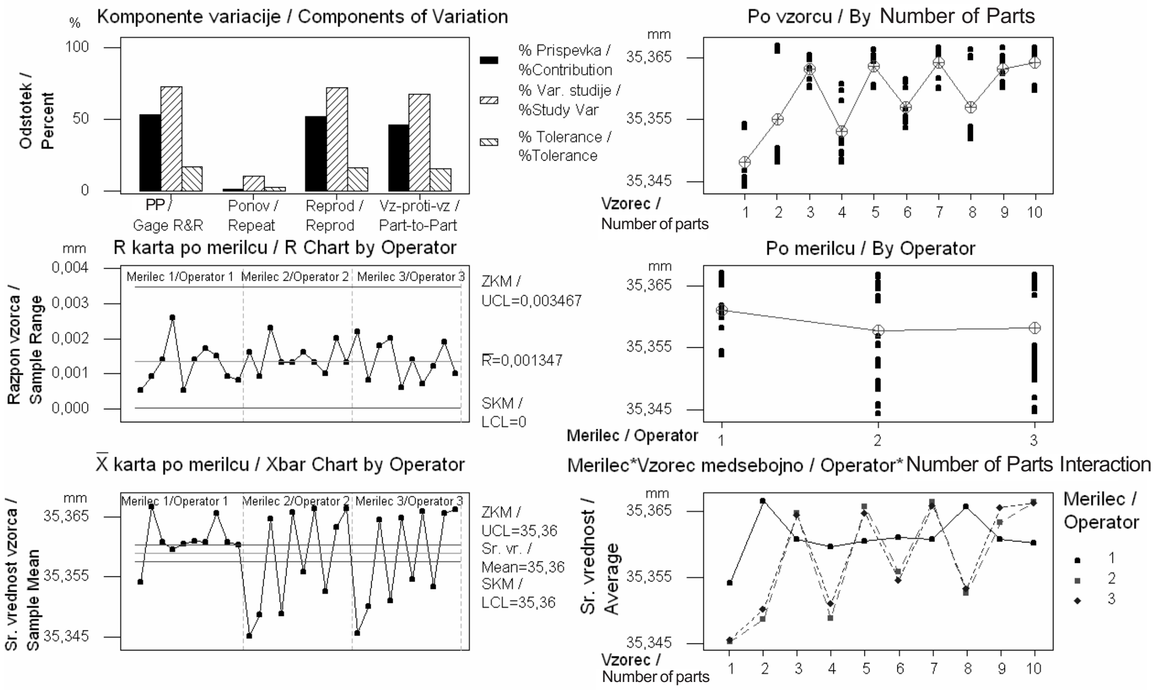
As can be seen in the flow chart in Figure 7, operator 1 measurements for several parts are significantly different from operator 2 and operator 3 measurements for the same parts.

The same conclusion can be drawn from Figure 8. As is show both on the $\overline{X}$ and R control charts, the measurements of operator 1 are quite different from the other two operators. This could mean that operator 1 is not adequately instructed for carrying out the planned measurements.

The gauge R&R analysis is shown in Figure 9. On the *Operator*Part numbers Interaction* diagram it is clear that the operator 1 measurements are significantly different from the other two operators and, consequently, the reproducibility is poor. At the same time, the repeatability is quite good, which leads to the conclusion that operator 1 should be better instructed in the measurement procedure. Furthermore, based on the gauge R&R analysis results, the measurement gauge appears to be appropriate for the planned measurements.



Sl. 8. *Kontrolna karta $\overline{X}$ - R za premer ϕ35,31±0,08 mm okrova turbo kompresorja*
Fig. 8. *$\overline{X}$ - R control chart for turbo-charger housing ϕ35.31 ± 0.08 mm*



Sl. 9. *Analiza PP*
Fig. 9. *Gauge R&R analysis*

3 SKLEPI

Merilni sistemi so v postopku zagotavljanja kakovosti zelo pomemben dejavnik. Če želimo izboljšati sistem kakovosti in dosegati zelo visoko raven zaupanja kupca v naše izdelke/storitve, moramo zelo resno jemati merilne sisteme kot komponente procesa, ki vplivajo neposredno na kakovost izdelka/storitve.

Če ne vemo zagotovo, kaj se dogaja z merilno opremo in v kakšni meri ji lahko zaupamo, tudi ne vemo zanesljivo, kaj se dogaja s kakovostjo procesa.

Probleme v proizvodnem procesu moramo reševati sistematično in zagotavljati najboljši mogoči način reševanja z ustrezno analizo merilnih sistemov.

Obstajajo različne metode v različnih primerih: od analize ponovljivosti, primerljivosti do zelo zapletene analize PP, ki skozi celotno analizo variacij sistema pokaže, kaj se s sistemom dogaja in kako moramo ukrepati, če je z njim kaj narobe.

Merilni sistem je kompleksen sistem, ki vključuje množico elementov, od merilnih naprav, človeka do vplivov okolja in podobno. Zato je zelo pomembno imeti pod nadzorom vse elemente, ki jih je mogoče obvladovati.

3 CONCLUSIONS

Measurement systems are a very important element in the quality-assurance process. To improve process quality and achieve a high level of customer confidence in products and services, measurement systems, which directly influence the products' quality, should become important components in the production processes.

If the measurement system error is unknown, the exact process quality level cannot be determined for sure.

Problems in the production process should be solved systematically using the best available process-improvement methods and an adequate measurement system analysis.

For a measurement system evaluation several methods are used, from simple repeatability and reproducibility analyses to complex gauge R&R analysis, which, through an in-depth analysis of measurement system variation, shows what is wrong with the measurement system and what action should be taken to correct existing problems.

A measurement system is a complex system that includes measurement gauges, but also the operators, the environment, etc. To ensure sound measurements and confidence in the measurement results, all the elements of the measurement system should be under control.

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Naslovi avtorjev: prof.dr. Mirko Soković
Univerza v Ljubljani
Fakulteta za strojništvo
Aškerčeva 6
1000 Ljubljana
mirko.sokovic@fs.uni-lj.si

doc.dr. Duško Pavletić
Univerza na Reki
Tehnična fakulteta
Vukovarska 58
HR-51000 Rijeka, Hrvaška
dusko.pavletic@riteh.hr

Romeo Matković
PC Cimos Buzet
Most 24
HR-52420 Buzet, Hrvaška

Authors' Addresses: Prof.Dr. Mirko Soković
University of Ljubljana
Faculty of Mechanical Eng.
Aškerčeva 6
SI-1000 Ljubljana, Slovenia
mirko.sokovic@fs.uni-lj.si

Doc.Dr. Duško Pavletić
University of Rijeka
Faculty of Engineering
Vukovarska 58
HR-51000 Rijeka, Croatia
dusko.pavletic@riteh.hr

Romeo Matković
PC Cimos Buzet
Most 24
HR-52420 Buzet, Croatia

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