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Methodology for Performing a Measurement System Analysis with Four Operators

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***Abstract*— A variety of factors have been shown to influence each measurement process, including environmental elements, the characteristics of the measured object, and the capabilities of the measuring instrument. These factors can be categorised into several overarching groups: external factors, the measurement object, the measuring instrument, and the operator. The present paper sets out a methodology for the evaluation of part quality in the domain of optical manufacturing. The methodology under discussion employs a measurement system analysis (MSA) method. Typically, MSA is applied to two or three operators; however, in this study, it is performed for four operators. In the course of the experiments, ten optical workpieces, lenses, are measured, with each lens undergoing three measurements. Each of the four operators measured the same set of lenses, employing the same measuring instrument. The measurement of identical parts and apparatus serves to eliminate the influence of the measuring instrument on the measuring system and to evaluate the influence of the operator. The objective of this work is to demonstrate the feasibility of employing MSA as a method for assessing the quality of more than three operators. To this end, four distinct analyses are implemented to assess the influence of each operator in relation to the others.**

Keywords*— *Adapted MSA, Lens, Measurement system analysis (MSA), Optical production, Quality control, Quality assessment.

I. INTRODUCTION

Measurement Systems Analysis (MSA) and Gauge Repeatability and Reproducibility (R&R) studies are recognised as essential tools for the assessment of the precision and consistency of measurement systems [1]. The prevailing focus of such studies is on the evaluation of both repeatability (i.e. within-appraiser variability) and reproducibility (i.e. between-appraiser variability), with the utilisation of multiple appraisers often being limited to two or three [1]. However, scenarios involving additional appraisers, such as situations where subsets (e.g., 3-of-4 appraiser combinations) are analysed, introduce complexities that remain underexplored in the literature. It is imperative to comprehend the impact of subset configurations on reproducibility, particularly in high-stakes measurement contexts, such as those involving optical systems. These contexts present distinctive challenges, including sensitivity to environmental factors, nonlinear variability, and calibration dependencies [2,3]. The present paper aims to build on existing knowledge by identifying and analysing relevant methodologies for studying the effect of four appraiser subsets on optical system measurement R&R.

There is a paucity of studies that explicitly address subset-based analyses. A notable exception is Mikulová and Plura [4], who explore appraiser-specific contributions to measurement variability using Gaussian curve visualisations. Their work underscores the variability introduced when analysing 2-of-3 appraiser subsets, thereby establishing a foundation for comprehending appraiser-specific effects that could be expanded to encompass larger groups. In a similar vein, Hamada et al. [5] utilise Bayesian methods and a Balanced Incomplete Block Design (BIBD) to address destructive testing scenarios, where not all appraisers evaluate all objects. These approaches provide methodological insights that are pertinent to the analysis of incomplete appraiser combinations. Furthermore, Jarošová [6] employs D-optimal experimental design to optimise measurement allocations in R&R studies, with the potential to reduce the replication burden and address the common occurrence of unbalanced designs in subset configurations.

Optical systems are known to present additional complications in the context of MSA, a phenomenon attributable to their sensitivity to environmental conditions and calibration inconsistencies. In their study, Groš et al. [2] examined the issue of reproducibility in three-dimensional optical measurement systems. The researchers demonstrated that calibration choices, including filter selection, have a substantial impact on variability. As Fedoryszyn and Brzeziński [3] further emphasise, it is imperative to distinguish between system-induced variability and environmental or process influences in high-

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precision contexts such as casting. These sector-specific studies reveal challenges in analysing optical systems and underscore the need for tailored approaches when applying R&R methodologies.

Notwithstanding the foregoing advancements, extant literature does not directly address the analysis of four appraiser subsets in R&R studies for optical systems. As demonstrated in [4, 5, 6], methodologies for subset analyses provide foundational tools. However, the integration of these methodologies with optical system-specific challenges [2, 3] remains unstudied. This discrepancy underscores the necessity for the development of bespoke experimental designs and statistical models, such as Bayesian frameworks [5] or mixed-effects models [7], which can accommodate subset configurations and the distinct variability sources observed in optical measurements. The objective of this study is to leverage the extant methodologies and insights to adapt MSA and R&R studies for the analysis of four appraiser subsets in optical systems.

II. Materials and Methods

A. Materials

The data utilised for the measurement system analysis are obtained through lens measurements (Fig. 1). In view of the stringent precision demands for the optical components, it is imperative that all measurements are conducted within the laboratory environment on the factory premises. The execution of measurements is undertaken by personnel who have undergone specialised training. It is evident that, during the MSA, the diameter of Ø24 e8 is designated as the controlled dimension. As demonstrated in Figure 1, two diameters, designated as Ø24 e8 and Ø24 h8, are apparent. The former, designated as Ø24 e8, corresponds to a state prior to varnishing, while the latter, designated as Ø24 h8, corresponds to a state subsequent to varnishing. It is imperative that all measurements are conducted with a high-precision micrometer, as illustrated in Figure 2.

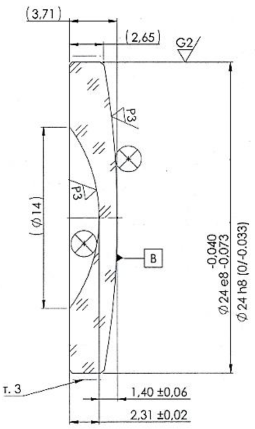

Fig 1. Measured optical detail

Fig 2. Measuring tool [8]

A. Methods

The evaluation of the results is conducted through the utilisation of measurement system analysis (MSA), a method that employs measurement data to assess the performance of a manufacturing process. For instance, the decision to adjust a manufacturing process is commonly based on measurement data. The data, or some of the statistics calculated from it, are then compared with the statistical control limits corresponding to the process. In the event that the comparison indicates that the process is out of statistical control, an adjustment is made. Conversely, if the comparison reveals that the process remains within statistical control, no adjustments are made [9].

The accuracy of measurement devices is defined as their capacity to generate output signals that approximate true values. The concept of accuracy measurement encompasses a multifaceted and substantial issue, namely the impact of repeatability of measurements and the contributions of individual operators. The influence of these elements on measurement methods is delineated through the R&R framework (Repeatability and Reproducibility). Conducting an R&R analysis necessitates the consideration of total variability, encompassing aspects such as repeatability, reproducibility, variability of components, and, most notably, variability of a single component or that arising from the permissible tolerance range [11].

Ishikawa's diagram shown in fig 3. illustrates the Measurement System Variability Cause and Effect Diagram.

In contrast to the prevailing approach to MSA, in which Workpiece, Instrument (Gage), and Person (Appraiser) are considered through their variations, namely Part Variation (PV), Equipment Variation (EV) (which is essentially Repeatability), and Appraiser Variation (AP) (which is essentially Reproducibility), GRR is described as the variance of the internal and external disturbances for the system, represented by the combined variance of repeatability and reproducibility [10].

In light of the aforementioned data, the MSA is executed employing the GRR method as delineated in the

4th Edition Reference Manual [9]. The ensuing values are thus derived:

Repeatability is equal to Equipment Variation:

$$EV = \bar{R} * K_1 \quad (1)$$

In accordance with the principles outlined in the “Measurement Systems Analysis Reference Manual”, the coefficient K_1 is selected from the provided table. K_1 depends on the number of trials in the used gage study [9].

Equipment Variation (EV) can be presented as %EV=100(EV/ Tolerance), where Tolerance is defined as the difference between the Upper Tolerance Limit (UTL) and the Lower Tolerance Limit (LTL).

Reproducibility is equivalent to Appraiser Variation (AV) [9]:

$$AV = \sqrt{(\bar{X}_{DIFF} * K_2) - \frac{EV^2}{nr}} \quad (2)$$

In accordance with the principles outlined in the “Measurement Systems Analysis Reference Manual”, the coefficient K_2 is selected from the provided table. K_2 depends upon the number of appraisers in the study [9].

The Appraiser Variation could be presented as follows: %AV=100(AV/Tol). The influence of the operator can be disregarded because it has an insignificant impact on the outcome if he performs his duties conscientiously.

$$GRR = \sqrt{EV^2 + AV^2} \quad (3)$$

and

$$\%GRR=100(GRR/Tol) \quad (4)$$

Part Variation:

$$PV = R_p * K_3 \quad (5)$$

In accordance with the principles outlined in the “Measurement Systems Analysis Reference Manual”, the coefficient K_3 are selected from the provided table. K_3 depends on the number of parts in the study [9].

Result could be presented as [9]:

$$\%PV= 100(PV/Tol) \quad (6)$$

It is imperative to note that all abbreviations utilized in the present document are in alignment with the Reference Manual, 4th Edition [9].

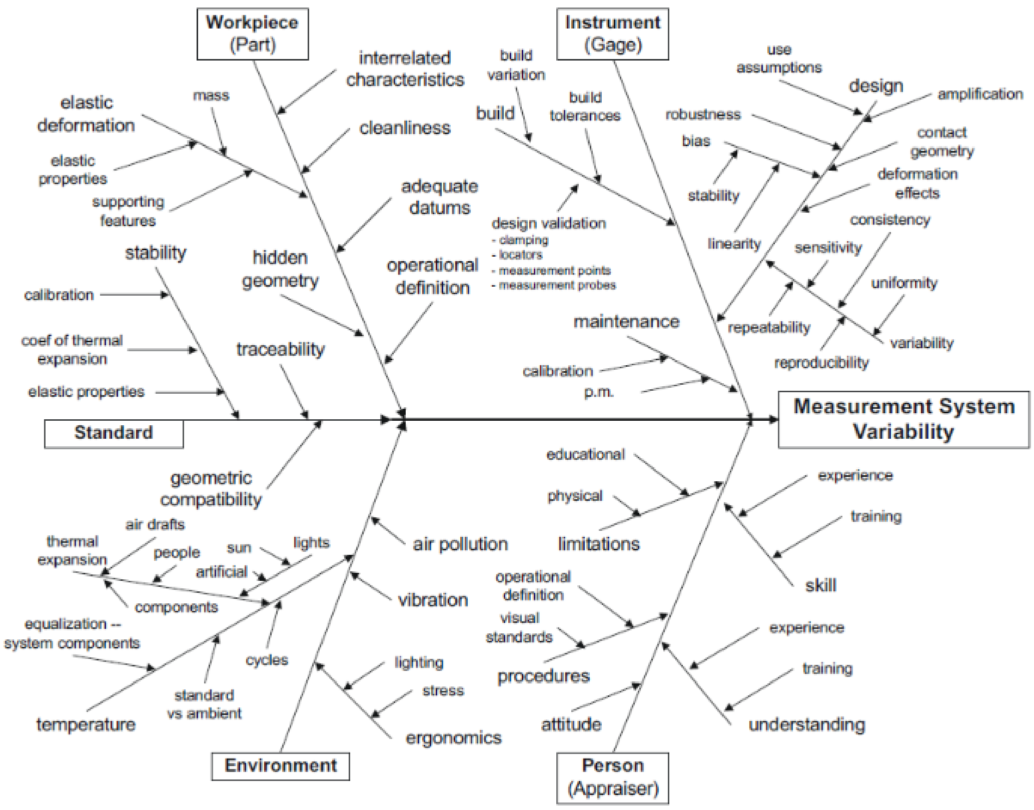

Fig. 3 MSA Cause and Effect Basic Diagram [11]

The MSA is a reliable statistical instrument for the evaluation of measurement systems; however, its application is currently limited to two or three operators. This paper proposes an extension of the MSA to a measurement system comprising four operators. The traditional method's restriction to three operators necessitates an adaptation. To apply the MSA to four operators, it is necessary to apply the known methodology for this analysis several times to cover all possible combinations of operators and to evaluate the impact of the operators on the measurement system. To limit the influence of the measuring instrument and the workpiece, the same ten lenses are measured three times each and the same measuring instrument is used.

III. Results and Discussion

The experiments were conducted by measuring 10 lenses each three times from all four operators. The measured diameter is Ø24 e8, with upper tolerance limit – 23.960, and lower tolerance limit – 23.927. The results of the measurements were recorded and used to conduct analyses. In order to evaluate the influence of the four operators on the measurement system, four standard MSAs were conducted so that all combinations were covered. The operators are denoted as A, B, C, and D, and the four sets of analyses performed are as follows: Series 1 - A, B, C; Series 2 - B, C, D; Series 3 - C, D, A; Series 4 - D, A, B. The results obtained are presented in the tables below.

TABLE 1. SERIES 1 DATA

APPRAISER/		PART										AVERAGE	
TRIAL #		1	2	3	4	5	6	7	8	9	10		
1. A	1	23,945	23,938	23,945	23,942	23,946	23,947	23,95	23,928	23,95	23,938		23,943
2,	2	23,943	23,936	23,942	23,943	23,946	23,946	23,949	23,928	23,95	23,94		23,942
3,	3	23,943	23,938	23,942	23,943	23,947	23,946	23,952	23,929	23,95	23,936		23,943
4,	AVE	23,944	23,937	23,943	23,943	23,946	23,946	23,950	23,928	23,950	23,938	X_a=	23,943
5,	R	0,002	0,002	0,003	0,001	0,001	0,001	0,003	0,001	0,000	0,004	r_a=	0,002
6. B	1	23,946	23,938	23,946	23,943	23,948	23,949	23,951	23,929	23,95	23,94		23,944
7,	2	23,945	23,936	23,944	23,942	23,947	23,946	23,952	23,927	23,952	23,941		23,943
8,	3	23,942	23,938	23,942	23,942	23,946	23,947	23,95	23,93	23,949	23,942		23,943
9,	AVE	23,944	23,937	23,944	23,942	23,947	23,947	23,951	23,929	23,950	23,941	X_b=	23,943
10,	R	0,004	0,002	0,004	0,001	0,002	0,003	0,002	0,003	0,003	0,002	r_b=	0,003
11. C	1	23,946	23,936	23,944	23,944	23,947	23,948	23,948	23,93	23,951	23,937		23,943
12,	2	23,944	23,937	23,943	23,941	23,944	23,949	23,951	23,928	23,95	23,939		23,943
13,	3	23,945	23,938	23,941	23,945	23,948	23,948	23,95	23,928	23,949	23,936		23,943
14,	AVE	23,945	23,937	23,943	23,943	23,946	23,948	23,950	23,929	23,950	23,937	X_c=	23,943
15,	R	0,002	0,002	0,003	0,004	0,004	0,001	0,003	0,002	0,002	0,003	r_c=	0,003
16. PART												X=	23,943
AVERAGE		23,94	23,94	23,94	23,94	23,95	23,95	23,95	23,93	23,95	23,94	R_p=	0,022
17,	$(r_a + r_b + r_c)$ / (# OF APPRAISERS) =											R=	0,002
18,	x_{DIFF} = (Max X - Min X) =											X_{DIFF}=	0,001
19,	* $UCL_R = R \times D_4$ =											UCL_R=	0,006

TABLE 2. SERIES 1 MSA RESULTS

Total Variation (TV)	Value
Repeatability - Equipment Variation (EV), %	19,71
Reproducibility - Appraiser Variation (AV), %	4,14
Repeatability & Reproducibility (GRR),%	20,14

The analysis of series 1 is shown at table 1 and table 2 demonstrates the variation of results in terms of instrument EV =19.71% (equipment variation) and operator AV (appraiser variation), with a value of 4.14%. The value of EV indicates the influence of equipment on the results, while the value of AV indicates a slight influence of the operator relative to the results obtained. According to the MSA standard is the GRR is less than 10%, so the measurement system is considered as acceptable. If the coefficient GRR is between 10% and 30% the system can be considered acceptable and consideration of riks, application and costs should be made. When GRR is more than 30% the measurement system is considered as unacceptable. The GRR (Gage Repeatability & Reproducibility) value of series 1 is 20.14%, so it indicates that the measurement system's results can be accepted as the GRR value is less than 30%.

Series 2 data and results are presented on table 3 and table 4.

TABLE 3. SERIES 2 DATA

APPRAISER/		PART										AVERAGE	
TRIAL #		1	2	3	4	5	6	7	8	9	10		
1. B	1	23,946	23,938	23,946	23,943	23,948	23,949	23,951	23,929	23,95	23,94		23,944
2,	2	23,945	23,936	23,944	23,942	23,947	23,946	23,952	23,927	23,952	23,941		23,943
3,	3	23,942	23,938	23,942	23,942	23,946	23,947	23,95	23,93	23,949	23,942		23,943
4,	AVE	23,944	23,937	23,944	23,942	23,947	23,947	23,951	23,929	23,950	23,941	X_a=	23,943
5,	R	0,004	0,002	0,004	0,001	0,002	0,003	0,002	0,003	0,003	0,002	r_a=	0,003
6. C	1	23,946	23,936	23,944	23,944	23,947	23,948	23,948	23,93	23,951	23,937		23,943
7,	2	23,944	23,937	23,943	23,941	23,944	23,949	23,951	23,928	23,95	23,939		23,943
8,	3	23,945	23,938	23,941	23,945	23,948	23,948	23,95	23,928	23,949	23,936		23,943
9,	AVE	23,945	23,937	23,943	23,943	23,946	23,948	23,950	23,929	23,950	23,937	X_b=	23,943
10,	R	0,002	0,002	0,003	0,004	0,004	0,001	0,003	0,002	0,002	0,003	r_b=	0,003
11. D	1	23,944	23,939	23,947	23,945	23,948	23,95	23,949	23,931	23,952	23,942		23,945
12,	2	23,946	23,938	23,945	23,944	23,946	23,947	23,95	23,929	23,949	23,943		23,944
13,	3	23,943	23,938	23,943	23,944	23,947	23,949	23,951	23,932	23,953	23,938		23,944
14,	AVE	23,944	23,938	23,945	23,944	23,947	23,949	23,950	23,931	23,951	23,941	X_c=	23,944
15,	R	0,003	0,001	0,004	0,001	0,002	0,003	0,002	0,003	0,004	0,005	r_c=	0,003
16. PART												X=	23,943
AVERAGE		23,94	23,94	23,94	23,94	23,95	23,95	23,95	23,93	23,95	23,94	R_p=	0,021
17,	$(r_a + r_b + r_c)$ / (# OF APPRAISERS) =											R=	0,003
18,	x_{DIFF} = (Max X - Min X) =											X_{DIFF}=	0,001
19,	* $UCL_R = R \times D_4$ =											UCL_R=	0,007

TABLE 4. SERIES 2 MSA RESULTS

Total Variation (TV)	Value
Repeatability - Equipment Variation (EV), %	22,89
Reproducibility - Appraiser Variation (AV), %	8,39
Repeatability & Reproducibility (GRR),%	24,37

EV = 22.89% and AV = 8.39%. The values of EV and AV are higher than the results from series 1. There is no big difference between the values of Equipment variation, they are very close. There is a significant difference between Appraiser variation from series 1 and series 2, the value in the series 2 is two times bigger than the EV from series 1. The GRR (Gage Repeatability & Reproducibility) value is 24.37% it is bigger than GRR in series 1, but it is still under 30%, so the measurement system is acceptable.

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The results from series 3 are shown in table 5 and table 6.

TABLE 5. SERIES 3 DATA

APPRAISER/ TRIAL #		PART 1	2	3	4	5	6	7	8	9	10	AVERAGE	
1. C	1	23,946	23,936	23,944	23,944	23,947	23,948	23,948	23,93	23,951	23,937		23,943
2,	2	23,944	23,937	23,943	23,941	23,944	23,949	23,951	23,928	23,95	23,939		23,943
3,	3	23,945	23,938	23,941	23,945	23,948	23,948	23,95	23,928	23,949	23,936		23,943
4,	AVE	23,945	23,937	23,943	23,943	23,946	23,948	23,950	23,929	23,950	23,937	X_a=	23,943
5,	R	0,002	0,002	0,003	0,004	0,004	0,001	0,003	0,002	0,002	0,003	r_a=	0,003
6. D	1	23,944	23,939	23,947	23,945	23,948	23,95	23,949	23,931	23,952	23,942		23,945
7,	2	23,946	23,938	23,945	23,944	23,946	23,947	23,95	23,929	23,949	23,943		23,944
8,	3	23,943	23,938	23,943	23,944	23,947	23,949	23,951	23,932	23,953	23,938		23,944
9,	AVE	23,944	23,938	23,945	23,944	23,947	23,949	23,950	23,931	23,951	23,941	X_b=	23,944
10,	R	0,003	0,001	0,004	0,001	0,002	0,003	0,002	0,003	0,004	0,005	r_b=	0,003
11. A	1	23,945	23,938	23,945	23,942	23,946	23,947	23,95	23,928	23,95	23,938		23,943
12,	2	23,943	23,936	23,942	23,943	23,946	23,946	23,949	23,928	23,95	23,94		23,942
13,	3	23,943	23,938	23,942	23,943	23,947	23,946	23,952	23,929	23,95	23,936		23,943
14,	AVE	23,944	23,937	23,943	23,943	23,946	23,946	23,950	23,928	23,950	23,938	X_c=	23,943
15,	R	0,002	0,002	0,003	0,001	0,001	0,001	0,003	0,001	0,000	0,004	r_c=	0,002
16. PART												X=	23,943
AVERAGE		23,94	23,94	23,94	23,94	23,95	23,95	23,95	23,93	23,95	23,94	R_p=	0,021
17,	$(r_a + r_b + r_c)$ / (# OF APPRAISERS) =											R=	0,002
18,	x_{DIFF} = (Max X - Min X) =											X_{DIFF}=	0,001
19,	* $UCL_R = R \times D_4$ =											UCL_R=	0,006

TABLE 6. SERIES 3 MSA RESULTS

Total Variation (TV)	Value
Repeatability - Equipment Variation (EV), %	20,66
Reproducibility - Appraiser Variation (AV), %	10,52
Repeatability & Reproducibility (GRR),%	23,18

In the 3rd series of the analysis the results shows EV = 20.66%, AV = 10,52 and GRR = 23.18%. A decline in the value of EV is observed, yet the coefficient AV exhibited an increase in comparison to the preceding two analyses. Gage Repeatability & Reproducibility is almost the same as GRR in series 2, the measurement system is still acceptable.

Data and results from the last series are shown on table 7 and table 8.

TABLE 7. SERIES 4 DATA

APPRAISER/ TRIAL #		PART 1	2	3	4	5	6	7	8	9	10	AVERAGE	
1. D	1	23,944	23,939	23,947	23,945	23,948	23,95	23,949	23,931	23,952	23,942		23,945
2,	2	23,946	23,938	23,945	23,944	23,946	23,95	23,95	23,929	23,949	23,943		23,944
3,	3	23,943	23,938	23,943	23,944	23,947	23,95	23,951	23,932	23,953	23,938		23,944
4,	AVE	23,944	23,938	23,945	23,944	23,947	23,949	23,950	23,931	23,951	23,941	X_a=	23,944
5,	R	0,003	0,001	0,004	0,001	0,002	0,003	0,002	0,003	0,004	0,005	r_a=	0,003
6. A	1	23,945	23,938	23,945	23,942	23,946	23,95	23,95	23,928	23,95	23,938		23,943
7,	2	23,943	23,936	23,942	23,943	23,946	23,95	23,949	23,928	23,95	23,94		23,942
8,	3	23,943	23,938	23,942	23,943	23,947	23,95	23,952	23,929	23,95	23,936		23,943
9,	AVE	23,944	23,937	23,943	23,943	23,946	23,946	23,950	23,928	23,950	23,938	X_b=	23,943
10,	R	0,002	0,002	0,003	0,001	0,001	0,001	0,003	0,001	0,000	0,004	r_b=	0,002
11. B	1	23,946	23,938	23,946	23,943	23,948	23,95	23,951	23,929	23,95	23,94		23,944
12,	2	23,945	23,936	23,944	23,942	23,947	23,95	23,952	23,927	23,952	23,941		23,943
13,	3	23,942	23,938	23,942	23,942	23,946	23,95	23,95	23,93	23,949	23,942		23,943
14,	AVE	23,944	23,937	23,944	23,942	23,947	23,947	23,951	23,929	23,950	23,941	X_c=	23,943
15,	R	0,004	0,002	0,004	0,001	0,002	0,003	0,002	0,003	0,003	0,002	r_c=	0,003
16. PART												X=	23,943
AVERAGE		23,94	23,94	23,94	23,94	23,95	23,95	23,95	23,93	23,95	23,94	R_p=	0,021
17,	$(r_a + r_b + r_c)$ / (# OF APPRAISERS) =											R=	0,002
18,	x_{DIFF} = (Max X - Min X) =											X_{DIFF}=	0,001
19,	* $UCL_R = R \times D_4$ =											UCL_R=	0,006

TABLE 8. SERIES 4 MSA RESULTS

Total Variation (TV)	Value
Repeatability - Equipment Variation (EV), %	20,56
Reproducibility - Appraiser Variation (AV), %	10,47
Repeatability & Reproducibility (GRR),%	23,07

Again, the coefficient EV = 20.56%, which is the same as the other three MSA analysis. The value of AV is 10,47%, and it is the same as the value of AV in the third series. GRR is 23,07%, again it is under 30%, so the system is acceptable.

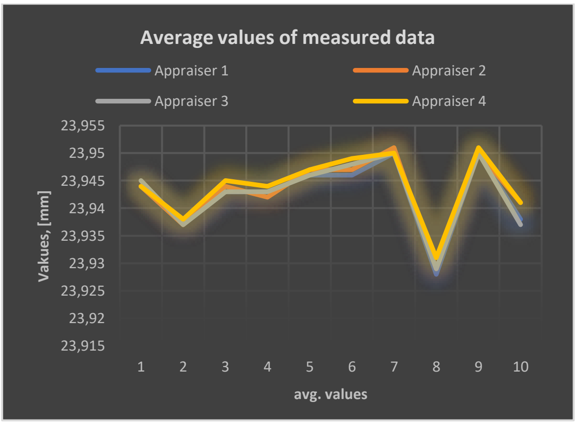

Fig. 4 avg values of measured data

Figure 4 shows a comparison between the average values of the four operators. The graphical representation of the results shows equivalent results for each operator, with no significant differences in their performance. illustrates the In summary the results from the first series show the best results overall. There are no significant changes in the EV values, they are all grouped in about 4%. Every measurement system is acceptable because the values of all GRRs are under 30%. The most notable change is observed when operator A is substituted by operator D, resulting in a doubling of the value of AV.

IV. Conclusions

The paper presents the flexibility of MSA, and how it can be adapted to different situations. Measurement system analysis is suitable for evaluating measurement systems with more than three appraisers. The equipment's influence on the measurement system is presumed to be constant, as evidenced by the similarity in the resulting EV values. The values of the Gage Repeatability & Reproducibility indicators for all four analyses are found to be less than 30%, indicating that the measurement system is acceptable. Due to the values of GRR between 10% and 30% a consideration should be given of risk, appliance and cost. The analyses indicate that operator A's measurements are the most consistent, and the analyses with his participation demonstrate a reduced operator influence on the measurement system. Through MSA, the influence of a specific operator on the measurement system can be determined.

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