STUDY OF THE IMPACT OF ILLUMINATION LEVEL ON ATTRIBUTATIVE MEASUREMENT SYSTEM AT AN AUTOMOTIVE INDUSTRY ENTERPRISE

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Abstract. Measurement System Analysis (MSA) is a critically important component of any quality improvement process and is formulated as an experimental and mathematical method for determining how much variation in the measurement process affects the measurement system, which in turn contains such data categories as: attributive or variable. Most of the problems of the measurement system arise precisely due to the assessment of attributive features, which are usually the result of subjective judgment (visual inspection). Since attribute measurement systems are often used in production processes, their evaluation is important for increasing reliability in the inspection process in order to determine the cause and source of the problem and in the future eliminate them and direct efforts to improve the process.

The authors investigated the influence of working environment parameters, namely the level of illumination, on the degree of correctness of the assessment of defects in cable product samples. The degree of conformity of evaluators with the established requirements was also assessed. MINITAB and Q-DAS solara.MP software were used to analyze the research results. The authors formulated recommendations for improving the accuracy of the functioning of the attribute measurement system at an automotive industry enterprise.

Key words: measurement system, attribute, evaluation, assessment, consistency, Cohen’s kappa statistics.

1. Introduction

To produce quality products, an enterprise must use quality resources or raw materials, which is not always achievable, because it is practically impossible to ensure 100 % quality of all resources or raw materials. But, only high-quality raw materials and the production of high-quality products that meet consumer demand and requirements should reach realization [1]. Every manufacturing company collects a large amount of data about systems and processes every day. Then this data affects decision-making in all areas of the company, including personnel policy, logistics and environmental elements. Information about the values of parameters should be objective, and therefore, be obtained through measurements [2]. A measurement system is a set of operations, procedures, measuring instruments and other equipment, software and personnel used to assign a number/degree (qualification, classification) to the characteristics being measured/classified; the complete process used to obtain measurements [3]. The quality of measurement information is reduced due to errors in the measurement system, which leads to incorrect decision-making [4]. Thus, measurement systems require analysis of their characteristics. Measurement system analysis is an experimental and mathematical approach that determines the number of variation that exists in a measurement process and minimizes the factors that influence the process variation that actually originate from the measurement system.

MSA is one of the most important quality tools used to evaluate the adequacy of variation in order to ensure the quality of a measurement system and related products. The goal is to quantify the accuracy, precision, and stability of a measurement system [5].

MSA is used in 98 % of projects, and it alone can have a huge impact on the success of any project and improvement in an organization. Measurement system analysis uses scientific principles to help teams analyze how much variation a measurement system introduces into a production process. MSA is important for: establishing the percentage of variation in a process that is caused by a measurement system; comparing processes and measurement results between operators (evaluators, inspectors); comparing measurement results between two (or more) measuring instruments; providing criteria for implementing new measurement systems; evaluating a suspect object; evaluate the gauge before and after repair; determine true process variability; evaluate the effectiveness of the training program.

The accuracy of a measurement system is based on two important characteristics – repeatability and reproducibility. Repeatability is usually related to the variation of equipment characteristics, and reproducibility is usually related to the variation of operator or inspector characteristics. During product inspection, the evaluator may accept bad parts as good (risk to the consumer) and good parts as bad (risk to the manufacturer), which will lead to higher costs, more rejections, and more customer complaints.

An attributive measurement system refers to a type of measurement system used to assess the presence or absence of certain attributes or characteristics of an object, element, or phenomenon. An attribute is a qualitative measure of a property of interest. An attribute can be represented by a binary definition (pass / fail, good / bad) [7]. In this system, items are typically classified as “good” or “bad,” “defective” or “defective-free,” or other binary classifications based on certain criteria or features. The attributive features are detected during appropriate visual inspection. Measurements in such cases are typically qualitative rather than quantitative (yes / no).

2. Disadvantages

Attributive measurement systems can face problems that are caused by environmental factors. These problems often occur because changes in environmental conditions can introduce variability and/or inconsistency into the measurement, affecting the reliability and accuracy of the data obtained. Key influencing factors include vibration, temperature, humidity, dust, noise. One of these is the level of illumination. Changes in illumination can significantly affect the results of visual inspection. Therefore, many authors focus on studying this issue by improving the ergonomics of workplaces [8], using simulation tools [9], by assessing the efficiency of the workplace [10–12]. However, for attributive systems, it is particularly important to investigate the impact of lighting level, as it affects the correctness of attribute classification based on visual characteristics. Environmental factors can significantly affect the accuracy and reliability of attribute measurement systems. Their detection and minimization are key to ensuring consistent and accurate measurements.

3. Purpose

The purpose of this article was to investigate the impact of the lighting level on attributive measurement systems at a cable network manufacturing enterprise for the automotive industry.

4. Research methodology

The study of the attribute data of the measurement system allows us to recognize and understand errors during data collection.

To conduct an attributive MSA study, you need to perform the following 5 steps:

1. Identify the inspection attribute that needs to be evaluated and analyzed. You need to have a clear and objective definition of what is considered “good” or “not good” for the sample being evaluated.

2. Select the measurement system to be used for the evaluation, which consists of the instrument, method, and operator performing the measurements.

3. MSA study planning – number of inspections, number of evaluators, determination of the sample size and its representativeness, which cover a wide range of variations for the attribute. For maximum confidence, a 50–50 combination of good/bad samples is recommended. A common approach is to analyze the attributive feature regarding the consistency of the evaluator, between evaluators, and between evaluators and references (standards).

4. Analyze MSA data – use statistical tools such as Excel, Minitab or Q-DAS solara.MP to perform and calculate agreement metrics for the measurement system. The main metrics are the percentage of agreement between raters, kappa statistics.

5. Improve the measurement system – identify sources of deviations and errors in the measurement system, take corrective actions to eliminate or reduce them.

The tool used for this analysis of attribute measurement systems is Gage R&R (repeatability and reproducibility), which means repeatability and reproducibility. In this case, repeatability means that the same operator working with the same object, using the same attribute, should obtain the same evaluation results. Reproducibility means that different operators measuring the same object, using the same attribute, should obtain the same values every time. Unlike the analysis of variable data in measurement systems, which deals with measurable quantities that can vary within a certain range, attributive R&R aims to ensure consistency and accuracy in the classification of items into categories. Gage R&R for attribute measurement systems involves calculating (in Minitab) two important metrics: percent repeatability and percent reproducibility. Additional analysis software products, such as Q-DAS solara.MP and its MSA ANOVA scoring strategy, can also be used.

The study will ensure that the measurement system is accurate and reliable for making decisions based on the classification of items. Consistency in the interpretation of attribute features by all raters will be critical to success. This methodology helps ensure that any decisions based on these measurements are reasonable and based on a reliable and reproducible system.

5. Research on Attribute Measurement Systems

The main production processes at a cable manufacturing plant include the crimping process. The majority of these operations occur in the cutting section. Crimping is a process used to create a safe and reliable connection between a wire and a contact by crimping. The operations are performed using cutting machines and crimping machines. One of the primary operations for controlling the crimping process is visual inspection, which aims to check for defects such as cratches, dents, and irregularities, as well as the presence of crimped wire strands on the contact connection, classifying them as “good” (defect-free) or “not good” (defective).

Through visual inspection, they evaluate the sample for the crimped wire strand over the contact. Thus, if wire strands are found over the crimp, it corresponds to a “not good” (not OK) assessment; otherwise, it is classified as “good” (OK). The visual inspection process was conducted under different lighting conditions to study its impact on the results of attributive measurements.

According to EN 12464-1:2021 [13], the main requirements for indoor lighting should correspond to the tasks and depend on the nature of the work:

A. industrial workplaces – from 200 to 500 lux;

B. detailed or precise work – from 500 to 1000 lux or higher;

C. tasks requiring high visual acuity (e.g. laboratory work, fine assembly) – usually 1000 lux or higher [8].

The studies were carried out for workers whose work can be classified as category B) (detailed or precise work – from 500 to 1000 lux or higher). 50 samples from the production batch were selected for the study. The sample consisted of 25 non-defective parts (good) and 25 defective parts (not good), which provides a balanced proportion for evaluation. 3 inspectors were selected for the study, each of whom checked all 50 samples three times: in the morning, at lunchtime and at the end of the work shift. Thus, each evaluator carried out 150 checks, and the total number of assessments was 450. The illumination level was measured with a calibrated digital luxmeter.

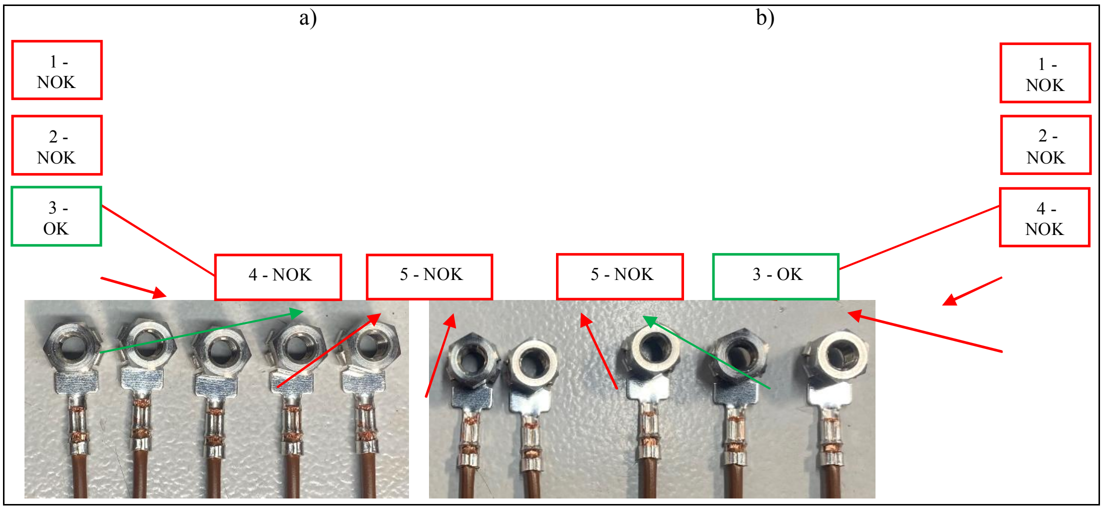


Fig. 1. Crimped contacts with different illumination levels: a – 700 lux; b – 1600 lux

Table 1. Evaluation criteria

Indicator	Acceptable	Marginally acceptable	Unacceptable
Individual repeatability	> 90 %	80 % to 90 %	< 80 %
Individual efficiency (each rater relative to the reference)	> 90 %	80 % to 90 %	< 80 %
Incorrect classification _ false negative result (reference “not good” rated as “good”)	< 2 %	2 % to 5 %	> 5 %
Incorrect classification _ false positive result (reference “good” rated as “not good”)	< 5 %	5 % to 10 %	> 10 %
Measurement system reproducibility (between raters)	> 90 %	80 % to 90 %	< 80 %
Overall measurement system efficiency (all raters relative to the reference)	> 90 %	80 % to 90 %	< 80 %
Cohen’s kappa statistic	>0.75	0.40 to 0.75	<0.40

In general, the following indicators were analyzed to assess the reliability of the measuring system:

1) repeatability – the difference in assessments made by the same inspector on the same part;

2) reproducibility – the difference in the assessments made by different inspectors on the same part;

3) combined variation from repeatability and reproducibility – the analysis focuses on determining what proportion of the observed variation in the results is due to the influence of illumination;

4) Cohen’s Kappa statistic – the level of agreement between the assessors; the level of agreement between each assessor and the reference.

The assessment criteria are presented in Table 1.

Another stage of the research was the comparison of the results obtained for different levels of illumination.

The results of the visual inspection were evaluated using Minitab software (Attribute Agreement Analysis module) [14]. The QS-STAT / SOLARA.MP software and its MSA ANOVA estimation strategy [15] were used to calculate Cohen’s kappa coefficient.

In Fig. 2, on the left, you can see the estimate of the level of agreement between the raters (repeatability analogy), and on the right, you can see the estimate of the level of agreement between the raters and the standard. The dots indicate the actual agreement for each rater, and the crosses indicate the prediction limits of the 95 % confidence interval for the mean agreement.

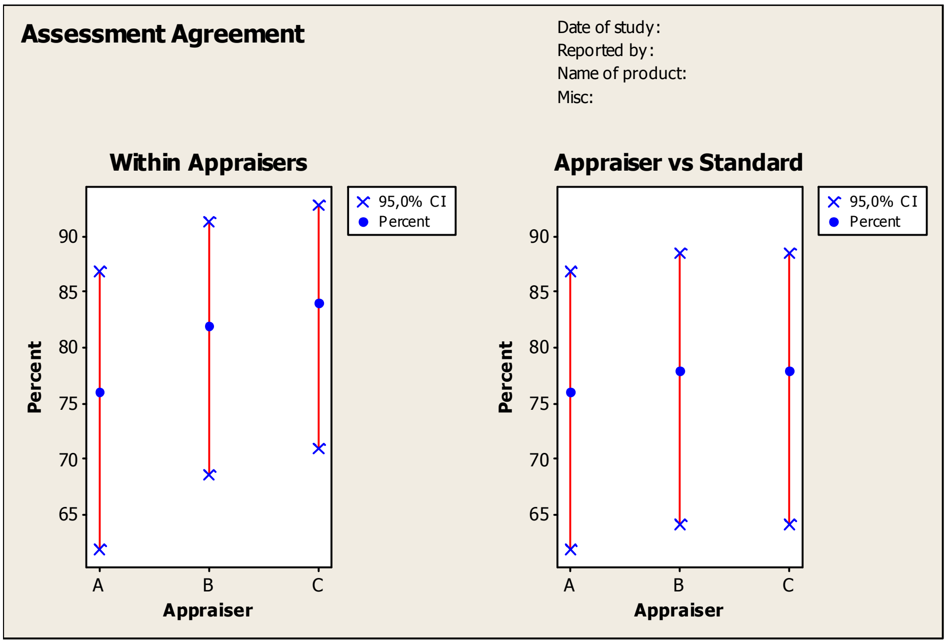


Fig. 2. Minitab Graph – Estimated Agreement (700 lux test)

Table 2. Individual Repeatability – 700 lux light level

Individual Repeatability			
Rating Agreement			
Estimator	Verified	Coincidences	%
A	50	38	76
B	50	41	82
C	50	42	84

Table 3. Individual Performance – 700 lux light level

Individual Performance			
Rating Agreement			
Estimator	Verified	Coincidences	%
A	50	38	76
B	50	39	78
C	50	39	78

Table 4. Misclassification – 700 lux illuminance

Each rater compared to standard results			
Misclassification			
Estimator	**A**	**B**	**C**
False positive results (Miss Rate)	4	9	7
Total rated as NOK	75	75	75
False negative results (False Alarm Rate)	10	7	11
Total rated as OK	75	75	75
False positive results (Miss Rate)	5.3	12.0	9.3
False Negative Results (False Alarm Rate)	13.3	9.3	14.7

Table 5. Reproducibility of the measurement system – 700 lux

Between the evaluators' results		
Rating Agreement		
Verified	Coincidence	%
50	28	56

Table 6. Efficiency of the measurement system – 700 lux illuminance

Between the evaluators' results and the reference		
Rating Agreement		
Verified	Coincidence	%
50	28	56

Analyzing the results of the study presented in Tables 2 – 6, the following conclusions can be drawn:

1) among raters (individual repeatability) is 76 %, 82 % and 84 % for raters 1, 2 and 3 respectively (left part of Fig. 2 and Table 2), therefore this means that these raters are not consistent in their assessments;

2) each rater compared to the reference (individual efficiency) is less than 80% for all raters, therefore unacceptable (right part of Fig. 2 and Table 3);

3) the results of the discrepancy assessment or misclassification (Table 4) show that all raters exceeded the 5 % threshold when classifying "not good" as "good"; as for the classification "good" that was assessed as "not good", two out of three raters were in the "red box", indicating unequivocal unacceptability;

4) the results between raters (reproducibility of the measurement system) show that all three raters agreed with each other on the three assessments only 28 times out of 50 assessed samples or 54 %, which also indicates unacceptability (Table 5);

Cohen's Kappa
Within and between appraisers

Operator	k	k	SEk	Z	P
A	--- 953	0 0.75	--- 953	--- 953	--- 953
B	--- 953	0 0.75	--- 953	--- 953	--- 953
C	--- 953	0 0.75	--- 953	--- 953	--- 953
A x B	0.681	0 0.75	0.0812	8.384	0.000
A x C	0.705	0 0.75	0.0816	8.643	0.000
B x C	0.627	0 0.75	0.0814	7.706	0.0000000000000655

			Evaluation category
Number of reference parts	=	50	0 / not OK 1 / OK
Number of operators	=	3	
Number of trials per operator	=	3	
Number of reference measurements	=	1	
Number of evaluation categories	=	2	
$Kappa_{Co}$ = K'_{Co}	=	0.6272	0 0.75
The requirements were not met (min, k_{FI})			

Cohen's Kappa versus Reference
Within and between appraisers

Operator	k	k	SEk	Z	P
A	0.813	0 0.75	0.0814	9.993	0.000
B	0.787	0 0.75	0.0816	9.638	0.000
C	0.760	0 0.75	0.0815	9.321	0.000
All operators	--- 955	0 0.75	--- 955	--- 955	--- 955

			Evaluation category
Number of reference parts	=	50	0 / not OK 1 / OK
Number of operators	=	3	
Number of trials per operator	=	3	
Number of reference measurements	=	1	
Number of evaluation categories	=	2	
$Kappa_{Co}$ = K'_{Co}	=	0.6272	0 0.75
The requirements were not met (min, k_{FI})			

Fig. 3. Q-DAS solara.MP report – calculation of the overall Kappa coefficient of agreement (study at 700 lux)

5) as for the overall performance of the measurement system (between raters and reference), like the previous indicator, it indicates critical unacceptability – only 56 % (Table 6);

6) analysis using the Q-DAS solara.MP software (Fig. 3), calculates the overall Kappa coefficient: $Kappa_{CO}=$ $= 0.6272$, so the measurement system is not acceptable.

Therefore, after the initial study, it can be concluded that the assessment results do not meet the established requirements. Moreover, the assessment results worsened with each subsequent attempt. This could be due to the assessor's visual fatigue during the shift.

The next study was conducted according to the previous methodology, but at an illumination level of 1600 lux.

The results are presented in Fig. 3 and Tables 7 – 11. It should be noted that the individual repeatability and individual efficiency of the assessors increased to 96 %, 98 % and 94 %, respectively, for assessors A, B and C, so the agreement is close to ideal (Fig. 4, Tables 7 and 8).

The results of the assessment of discrepancies or misclassification, presented in Table 8, demonstrate that only 2 times the "not good" sample was assessed as "good" or the two assessors made 1.3 % errors each at an acceptable level of 2 %. Regarding false negative results (False Alarm Rate) – 1.3 %, 1.3 %, 2.7 % according to evaluators A, B, C with an acceptable 5 %.

The reproducibility and overall efficiency of the measurement system was 92 %, which clearly indicates its unquestionable acceptability.

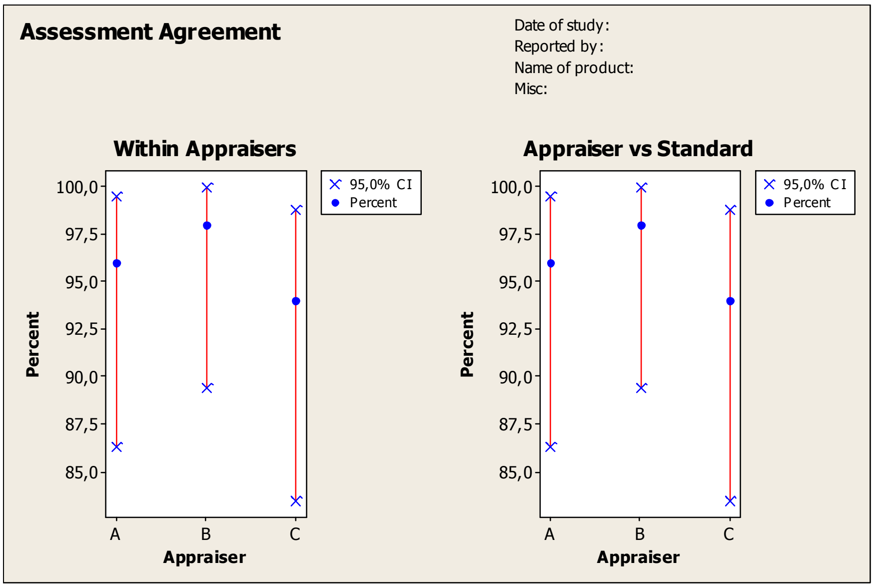


Fig. 4. Minitab graph – Estimation of the level of consistency (study at an illumination level of 1600 lux)

Table 7. Individual Repeatability – 1600 lux light level

Individual Repeatability			
Rating Agreement			
Estimator	Verified	Coincidences	%
A	50	48	96
B	50	49	98
C	50	47	94

Table 8. Individual Performance – 1600 lux light level

Individual Performance			
Rating Agreement			
Estimator	Verified	Coincidences	%
A	50	48	96
B	50	49	98
C	50	47	94

Table 9. Misclassification – 1660 lux illuminance

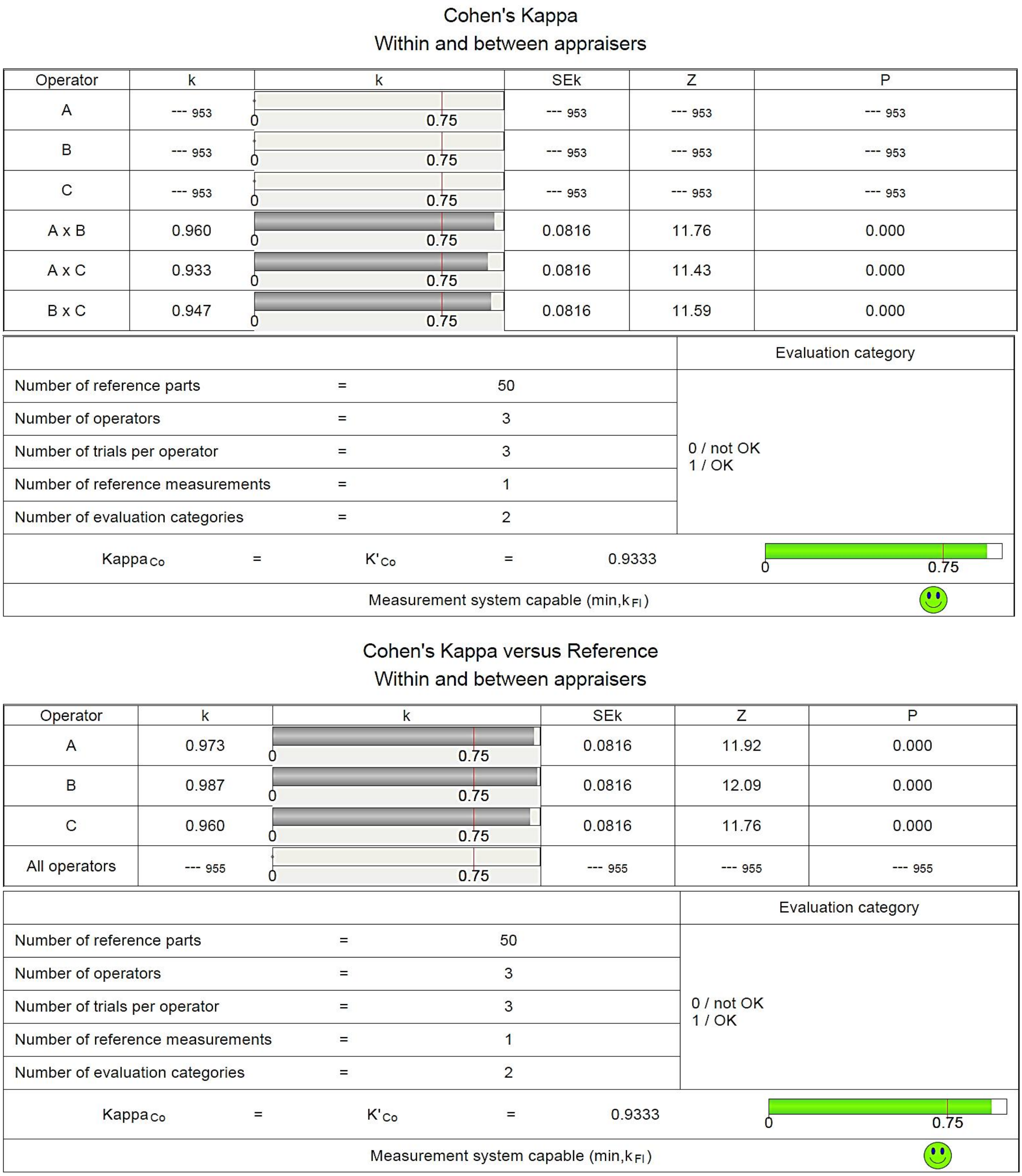
Each rater compared to standard results			
Misclassification			
Estimator	**A**	**B**	**C**
False positive results (Miss Rate)	1	0	1
Total rated as NOK	75	75	75
False negative results (False Alarm Rate)	1	1	2
Total rated as OK	75	75	75
False positive results (Miss Rate)	1.3	0.0	1.3
False Negative Results (False Alarm Rate)	1.3	1.3	2.7

Table 10. Reproducibility of the measuring system – illumination level – 1600 lux

Between the evaluators' results		
Rating Agreement		
Verified	Coincidences	%
50	46	92

Table 11. Measuring system efficiency – illumination level – 1600 lux

Between the evaluators' results and the reference		
Rating Agreement		
Verified	Coincidences	%
50	46	92



Cohen's Kappa
Within and between appraisers

Operator	k	k	SEk	Z	P
A	--- 953	0 0.75	--- 953	--- 953	--- 953
B	--- 953	0 0.75	--- 953	--- 953	--- 953
C	--- 953	0 0.75	--- 953	--- 953	--- 953
A x B	0.960	0 0.75	0.0816	11.76	0.000
A x C	0.933	0 0.75	0.0816	11.43	0.000
B x C	0.947	0 0.75	0.0816	11.59	0.000

			Evaluation category
Number of reference parts	=	50	0 / not OK 1 / OK
Number of operators	=	3	
Number of trials per operator	=	3	
Number of reference measurements	=	1	
Number of evaluation categories	=	2	
$Kappa_{Co}$ = K'_{Co}	=	0.9333	0 0.75
Measurement system capable (min, k_{FI})			

Cohen's Kappa versus Reference
Within and between appraisers

Operator	k	k	SEk	Z	P
A	0.973	0 0.75	0.0816	11.92	0.000
B	0.987	0 0.75	0.0816	12.09	0.000
C	0.960	0 0.75	0.0816	11.76	0.000
All operators	--- 955	0 0.75	--- 955	--- 955	--- 955

			Evaluation category
Number of reference parts	=	50	0 / not OK 1 / OK
Number of operators	=	3	
Number of trials per operator	=	3	
Number of reference measurements	=	1	
Number of evaluation categories	=	2	
$Kappa_{Co}$ = K'_{Co}	=	0.9333	0 0.75
Measurement system capable (min, k_{FI})			

Fig. 5. Q-DAS solara.MP report – calculation of the overall Kappa coefficient of agreement (illuminance level 1600 lux)

Based on the application of Kappa statistics (Fig. 5), the Kappa coefficient value was calculated: $Kappa_{CO}$ = = 0.9333. Conclusion – the measurement system is suitable.

An additional study was conducted with an illumination level of 2500 lux. The results are presented below in Tables 12–16.

Table 12. Individual Repeatability – 2500 lux light level

Individual Repeatability			
Rating Agreement			
Estimator	Verified	Coincidences	%
A	50	49	98
B	50	48	96
C	50	49	98

Table 13. Individual Performance – 2500 lux light level

Individual Performance			
Rating Agreement			
Estimator	Verified	Coincidences	%
A	50	49	98
B	50	48	96
C	50	49	98

Table 14. Incorrect classification – illumination level – 2500 lux

Each rater compared to standard results			
Misclassification			
Estimator	**A**	**B**	**C**
False positive results (Miss Rate)	1	0	1
Total rated as NOK	75	75	75
False negative results (False Alarm Rate)	0	2	0
Total rated as OK	75	75	75
False positive results (Miss Rate)	1.3	0.0	1.3
False Negative Results (False Alarm Rate)	0.0	2.7	0.0

Table 15. Reproducibility of the measuring system – illumination level – 2500 lux

Between the evaluators' results		
Rating Agreement		
Verified	Coincidences	%
50	46	92

Table 16. Measuring system efficiency – illumination level – 2500 lux

Between the evaluators' results and the reference		
Rating Agreement		
Verified	Coincidences	%
50	46	92

Table 17. Dependence of the illumination level of the evaluation object on the distance to the light source

Distance from the light source to the object of evaluation, cm	Illumination level, lux
10	15000
15	11000
20	8800
25	7000
30	5800
35	5200
40	4500
45	4000
50	3500
55	3150
60	2800
65	2560
70	2320
75	2150
80	1940
85	1850
90	1780
95	1700
100	1500

According to the results of the research (Tables 12 – 16), it was concluded that when the illumination level was increased to 2500 lux, the overall efficiency of the measuring system remained at the same level as at 1600 lux. This may be due to the fact that when the illumination level increases, the gloss of the metal surface increases and the image does not improve. In addition. It should be remembered that excessive illumination accelerates the visual fatigue of the evaluator. The authors conducted a study of the dependence of the illumination level of the evaluation object on the distance to the light source (Table 17), on the basis of which the optimal distance of the evaluation object relative to the light source was established – 95–100 cm.

5. Conclusions

The results of the study showed that optimal lighting conditions have a significant positive effect on the attributive measurement system. Individual repeatability (variation within one rater) and individual efficiency (variation within one rater and reference) increased on average from 80 % (under 600 lux) to 96 % (under 1600 lux). This indicates that raters were more consistent during the inspection under improved lighting. The reproducibility (between raters) of the measurement system increased from 56 % to 92 %, indicating that inter-rater agreement was significantly better at 1600 lux. The overall efficiency (between raters and reference) of the measurement system was 92 % under the optimal 1600 lux. The Kappa statistics showed a significant increase from 0.6272 (partial acceptability) to 0.9332 (full acceptability), which also indicates a noticeable increase in the consistency of assessments with increasing illumination level. Further increase in illumination level to 2500 lux did not show better results. That is, the efficiency of the measuring system did not increase. Based on the study of the dependence of the illumination level of the evaluation object on the distance to the light source, the authors established the optimal distance of the evaluation object from the light source – 95–100 cm.

Analysis of the measurement system by attributes is an effective tool that an organization can use to better understand its processes of control and verification of the reliability of data obtained using measurement systems. Optimization of the illumination level in attribute measurement systems increases their accuracy, efficiency and versatility. It ensures correct assessments by reducing external interference such as glare or shadows, improves real-time data processing and allows for better detection of defects, which is crucial for many modern measurement tasks, the solution of which is important to maintain high standards of control.

Conflict of interest

The authors declare that there are no financial or other potential conflicts of interest regarding this work.

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