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POLSKA AKADEMIA NAUK

Management and Production Engineering Review
Volume 14 • Number 4 • December 2024 • pp. 1–18
DOI: 10.24425/mper.2024.153115

mper

Assessment of the Implementation of a 3D Vision Measuring System on the Production Line in Quality Control of Refractory Products

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Received: 22 March 2024
Accepted: 25 July 2024

Abstract

The article is a case study on improving the production process of refractory products, where the results of the visual inspection processes of the tested product were used to initiate the improvement. The article presents a systemic process approach to measurement problems and its application using a 3D camera in the refractory industry. The article presents the analysis of the nonconformity structure of the tested product, based on which critical nonconformities were identified and corrective actions were initiated. Special attention was paid to the importance of metrological control (quality control plan) over the process of manufactured products. The requirements for measuring equipment according to quality standards were presented and the principles of their effective use in real conditions were discussed. The analyses carried out have shown that by analysing the results of quality control it is possible to reduce the occurrence of quality problems and thus improve the production process. The originality of the research lies in the identification of significant differences in the quality aspects of products. Research results can contribute to more effective and coherent development activities to achieve a stable and competitive advantage in the market by improving the quality and environmental performance of products. The research results and the conclusions drawn from them can be used by scientists and practitioners to shape the target states of companies in a period of growing commitment to the idea of sustainable production.

Keywords

3D camera, ANOVA, refractory products, FMEA method, quality control.

Introduction

Maintaining a fully stabilised manufacturing process and maintaining the highest product quality are the main concerns of manufacturing companies. High market requirements for product conformity force the use of production control and quality monitoring systems in production processes, ensuring constant monitoring of the final product. In many cases, it is necessary to monitor production at every level to ensure that the product meets customer requirements and technical specifications contained in standards. Building a system for automatic quality monitoring and data acquisition allows you to diagnose possible faults during the production process. Special tools and sensors are used to create monitoring systems that provide information on the necessary control parameters, adapted to the type of production, the measured values and the required control times. There are currently several dozen standardized management systems, and new ones are being developed all the time. Most of them are specialized industry systems based on the general concept contained in the ISO 9000 family of standards (Ostrowska, 2004). All of these standardized management systems include requirements for carrying out measurements. The required measurements usually cover the entire activity of the organization, both operational and management processes, although individual systems place different emphasis on selected areas. However, the results of measurements should always be analyzed and used to improve the company's activities (Antosz, 2012). The research presented an innovative concept of measuring the finished product, such as a ladle valve, as part of quality control. The measurements were then collected, processed and verified under real conditions.

The scientific objective of the work is to evaluate the implementation of an innovative system for scan-

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ning objects directly on the production line. The research aims to obtain reliable measurement data for the optimization of production processes. This study is a continuation of the research on the implementation of modern automation systems according to the concept of Industry 4.0. The research was carried out to demonstrate that the use of modern automation tools in the production process of refractory products will contribute to improving the quality of finished products, reduce production time and not harm the environment, which will bring measurable economic benefits. To the best of our knowledge, this is the first approach to the research topic analyzed in this market sector, which certainly represents an added value to the considerations presented.

The research was carried out using a company in the refractory industry as an example. The research period included the collection of measurement data both during the implementation of the system and after its launch. A detailed analysis of the implementation has been carried out, and conclusions have been drawn about important stages of the production process, as well as its limitations and advantages.

After reviewing the literature of the last 5 years, the authors noticed that researchers have not undertaken the implementation of the solutions presented to optimize and harmonize the production processes of refractory products. It is a diverse production process, which is why individual approaches to this type of project have always been used. This approach is very time-consuming and economically unjustified. Therefore, this article undertakes a case study and complements the research and analysis of the practical use of optimization tools to solve complex problems and design systems of the analyzed case.

The article provides a new perspective and complements the current literature in the fields of technology, automation, innovative technological solutions, circular economy, environmental protection and economics. The research presented complements the knowledge about the search for new ways of working and the role of people in industry, which is very important for the development of any company and the production of high-quality products.

The article is structured as follows. Section 2 contains a literature review of the research case analyzed. Section 3 provides a detailed description of the research approach. Section 4 describes the results of the experimental research and their interpretation. Section 5 presents the conclusions of the research, indicating its limitations, practical applications and future research directions in this area.

Literature review

Subject of study

The company studied is currently the world leader in the production of ceramics and refractories. It offers a wide range of products, metal flow control systems and technological solutions to customers around the world (Pietras, 2017). Its main customers are the metallurgical, foundry and steel industries, as well as the glass and solar energy industries. The company's policy is to actively eliminate customer problems and constantly improve the quality management system to take all measures to improve product quality (Terenowski, 2010; Binczyk & Świsulski, 2012). The goal was to ensure that none of the recipients received products that did not meet the required specifications (Kowalik, 2018). Another goal is to identify potential low quality at the earliest possible stage of production and to eliminate the repetition of errors.

The subject of the research is the ladle gate valve system (Wróblewski & Niekurzak, 2022). They are used to minimise secondary oxidation of steel and to regulate the flow of steel from the ladle to the tundish, which is designed to operate at high temperatures. Figure 1 shows the final product.

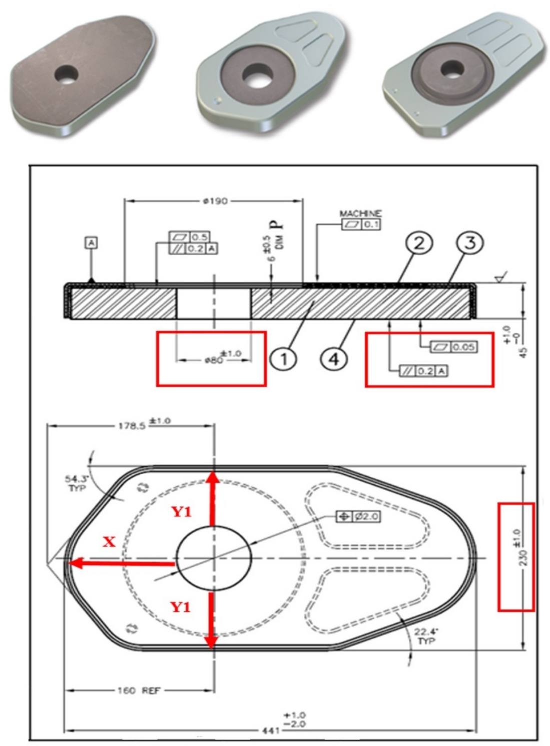

Fig. 1. The finished product and its technical specifications

High-quality refractory materials and designed structural applications are used in production. These systems help to reduce the ladle turnover time while ensuring more efficient ladle management (Wrona, 2014). As a result of their use, the total cost of ladle refractories is reduced along with the minimization of labour and energy (Islam & Chowdhury, 2017; Maurissen & Vidmar, 2017). The implemented series of tests allows crack control, prediction of thermomechanical behavior and control of the implementation of stress modelling elements in the plates to create an optimized refractory plate design (Stefanów, 2013). The analytical tests are used to introduce continuous improvements and solutions in terms of material performance, and the designs themselves are adapted to the specific requirements of individual customers. The key parameters for the client include:

- thickness
- parallelism
- flatness
- position of the hole relative to the axis: Y1, Y2, X,
- width.

The above measurements are carried out using basic tools such as:

- caliper
- straight edge and feeler gauge
- depth gauge.

Measuring system

By definition, a measurement system is a set of functional elements that form a whole. The system is used to obtain metrological data collected from the tested object and to provide useful information to the tester (Pająk & Diering, 2010). Currently, there is an increasing trend to adapt the system software and reduce the hardware part. Depending on their purpose, measurement systems can be divided into research, diagnosis and control (damage detection and location) (Bosley, 2019). A good measurement system gives the same or a very similar result for each dimension measured. The quality of the measurement system is a direct influence on the quality of the test. Quantities such as accuracy, which describes the position of the results relative to the actual data, and variability, which determines the range of the data, are used to describe the correct operation of the system (Szerszunowicz, 2013). The reasons for the differences between the desired and actual measurement results are variations, the sources of which can be found both in the processes and in the environment. The classification of the variability factors affecting the measurement result by type is shown in Figure 2.

It should be noted that the source of non-compliance can be any element related to the use of the measurement system (Kosiorek, 2013). Errors in the measurement system significantly distort data analysis. The entire measurement system consists of the operator's control methods, the measurement tools and the environment (Mikulik & Niekurzak, 2023). The influence of each of these elements can lead to variations in the measurement system, which are reflected in the process variability results during analysis and negatively affect the process capability.

Factors influencing measurement results

Man	Measurement object	Assessment method	Envirromment
– qualifications, – physical conditio, – mental conditio, – motivation, – discipline, – diligence.	– material, – shape, – surface, – availability.	– mathematical model, – computer use, – statistical method, – connection of measured values.	– lighting, – vibrations, – temperature, – humidity, – pollution.
Measurement method	Fixing device	Template	Measurement
– touch, – contactless, – arrangement of measurement points, – numer of measurement points.	– position, – location, – shape, – stability.	– surface, – type of pattern, – shape/position, – stability of the measuring instrument.	– calibration, – random measurement errors, – sensitivity, – measurement range, – stability, – load, – resolution.

Fig. 2. Division of factors influencing variability

Considering that the quality of the measuring system has a significant influence on the quality of the obtained results and that they are not error-free, an analysis of the measuring systems is carried out to identify their imperfections. Thanks to this, the level of reliability of the collected measurement data is known (Haverkamp & Beauducel, 2019). The quality of a measurement system is described by statistical properties. The following statistical properties have been distinguished and are used to evaluate the measurement system:

- Repeatability – repeatability testing provides an answer to the question of whether the same person, using the same instrument, will obtain the same result when making multiple measurements of the same parameter. Describes the variability of a single person's measurement.
- Reproducibility – tests whether the measurement result is the same when the same parameter is measured several times by several operators. Describes the variability between the measurements of several people.
- Accuracy – the difference between the reference (actual) value and the average result of measurements of the same parameter on the same element.
- Stability – represents the total variability for the same parameter of the tested variable over a longer period.
- Linearity – represents the difference in the value of the systematic error in a specific working range of the measuring instrument.
- Resolution – the value of the smallest change in the actual value of the measured parameter that can be distinguished by the measuring system.

The use of 3D cameras in the measurement system

The use of optical 3D digitization in metrology is becoming more common and desirable. Unfortunately, there are still no binding standards for measuring the uncertainty of these systems. 3D scanner manufacturers often use their standards to determine the accuracy of their devices (Niekurzak et al., 2023). Currently, dimension and shape measurement in industrial practice is carried out using conventional methods. Methods such as the contact method using coordinate measuring machines are increasingly being chosen. Although these machines provide some of the most accurate results, in some cases they cannot be used (Roszak, 2014). An example would be the measurement of surfaces with very complex shapes. For this reason, laser and optical measurement systems are increasingly being used by so-called 3D scanners. The use of these systems offers several important advantages, such as the fast measurement of parts, even with complex shapes, the independence of the results and the acquisition of large amounts of data. The general description of the measured part allows a comprehensive and objective analysis. The methods of using 3D scanners have been widely described in the relevant literature (Ullah, et al., 2022; Wróblewski, 2023; Yu, et al., 2023). The authors of the works (Mubashar, et.al., 2022) and (Wróblewski, 2023) use the examples of different industries to point out the advantages, limitations and possibilities of using this technology for different sectors of the economy. The 3D camera is a three-dimensional scanning system of the working space compatible with the production process (Rusecki, 2018). The main tasks of the vision system include the dimensioning of the examined object together with its classification of the correctness of the processing based on the specified tolerances (Król, 2020). The camera should be designed in such a way that it can become part of the direct work in connection with the production line. The scanner consists of a projector and two cameras. The scanners are housed in a sealed enclosure that protects them from unwanted damage such as dust and moisture. The use of blue structured light with a filter with a filtration coefficient of 95% allows almost complete suppression of the influence of external lighting conditions (Wyrębek, 2012). The scanner is characterized by high sensitivity when scanning objects with a matt and dark surface. Thanks to the isolation and filtration of extraneous light, it is possible to set a higher camera exposure. It also eliminates reflections when scanning dark or shiny surfaces. Scanners use structured light to map an object sequentially. To fully describe an object, it is necessary to take scans from two opposite directions (Wróblewski et al., 2023). For a given product to be measured, it is necessary to perform a scan and then create a measurement pattern in Geomagic Control. Once the scan is complete, a PDF report is generated. In addition, the report includes an image of the tested product (Fig. 3) along with the flatness cartography and all measurement parameters.

Materials & Methods

In the first part of the research, a cause and effect analysis, i.e. a risk assessment for the introduction of new technology, was carried out to identify factors that interfere with the measurement process. The analysis aimed to identify the possibility of undesirable actions occurring during the production process. An interdisciplinary group of five people was then

Thickness

Name	Tol.	Dev.	Ref. Value	Meas Value
Thickness 1	0 ∼ 1	0.4517	45	45.4517
Thickness 2	0 ∼ 1	0.6552	45	45.6552
Thickness 3	0 ∼ 1	0.4231	45	45.4231
Thickness 4	0 ∼ 1	0.4725	45	45.4725
Thickness 5 ref	0 ∼ 1	0.3828	45	45.3828
Thickness 6 ref	0 ∼ 1	0.6009	45	45.6009
Thickness 7 ref	0 ∼ 1	0.5332	45	45.5332

Flatness

Name	Tol.	Meas Value	RMS	Dev.
Can Flatness 1	0.05	0.2646	0.0598	0.0598
Surface flatness 2	0.018	0.0566	0.0136	0.0136

Hole

Name	Tol.	Dev.	Ref. Value	Meas Value
Bore position Y1	±1	–0.1551	85	84.8449
Bore diameter	±1	–0.1686	60	59.8314
Bore position Y2	±1	0.3723	85	85.3723

Gauge

Name	Tol.	Dev.	Ref. Value	Meas Value
Bore position Y1	±1	–0.1551	85	84.8449
Bore diameter	±1	–0.1686	60	59.8314
Bore position Y2	±1	0.3723	85	85.3723

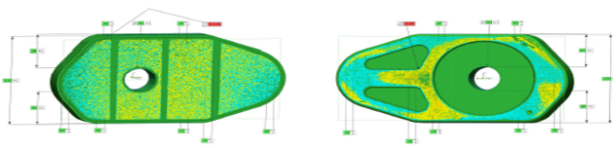

Fig. 3. Report generated in PDF format

set up, including the quality manager, the production manager, the maintenance manager, the operator and the production technologist. When characterising the non-conformities, the factors influencing the incorrect operation of the system were considered, i.e. the main mechanical elements, human influence, external factors and other undesirable events. After identifying the important elements, the effects of situations that hinder and prevent the correct operation of the system were indicated. Three criteria were determined, such as the significance of the defect, the probability of non-compliance and the level of detection of this non-compliance, by calculating the RPN non-compliance risk value. An RPN threshold of 35 was adopted, above which corrective action should be taken (Skotnicka-Zasadzień, 2012). The next step in the research was to perform an MSA – Measurement System Analysis.

The purpose of this analysis is to determine whether the results of the analyzed company are reliable and to determine the influence of the measurement system variability on the overall measurement variability. The study included an evaluation of measurements using standard measurement tools, such as a caliper gauge and a depth gauge, to verify a better method. The analysis of the results obtained using the vision system is presented and the variability for each method is compared. The bottleneck parameters, i.e. the critical parameters that affect the final quality of the product, were analyzed, i.e. the thickness and parallelism of the ladle gate system. The test aimed to verify that the current measurement methods are appropriate (acceptable), i.e. that they account for less than <30% of the total variability of the results. The test was performed under standard working conditions. As a representative sample, eight boards of the same type were used, representing the widest possible range of variability of the production process itself, and three measurement repetitions (blind and random) were used.

An R&R analysis was then carried out to measure repeatability and reproducibility using the Minitab application. This program uses the ANOVA method of analysis, which determines the percentage components of the variability of each element along with the total variability. ANOVA analysis was used to measure parallelism and thickness at four critical design points of the ladle gate system. The results of the ANOVA method were then presented for measurements made using the 3D camera. Five boards of the same type were used for the test, two of which were out-of-specification products (Stadnicka & Jastrzębski, 2015). According to the assumptions of the method, the guidelines for acceptance of the indicator are:

- R&R = < 10% – process capable
- R&R = < 30% and > 10% – process capable (can be improved)
- R&R = > 30% – process not capable (unacceptable).

The final stage was to calculate the process capacity to determine the stability and quality of the process under statistical control. The process capacity should be determined by taking into account two pairs of basic factors:

- C_p and C_{pk} – short-term capacity indicators
- P_p and P_{pk} – long-term capacity indicators.

These indicators differ mainly in the way they are collected. When calculating C_p and C_{pk}, it is optimal to use about 5 samples in order to observe the variability between them. The collected samples form the so-called subgroup. To calculate P_p and P_{pk}, the data should be collected over time without being divided into individual groups.

The C_p index is the potential capacity of the production process, which is the ratio of the width of the tolerance field to the width of the spread.

$$C_p = \frac{\text{UCL} - \text{LCL}}{6\sigma} \tag{1}$$

The standard deviation, which represents the internal variability of the process, should be calculated from the formula:

$$C_{pk} = \min\left\{\frac{\overline{x} - \text{LCL}}{3\sigma}; \frac{\text{UCL} - \overline{x}}{3\sigma}\right\} \tag{2}$$

$$\sigma = \frac{\overline{R}}{d_2} \tag{3}$$

where:

$graveR\overline{R}$ – mean value over the range of samples
d_2 – constant statistical coefficient
σ – standard deviation
LCL – lower tolerance limit
UCL – upper limit of tolerance

To assess the process capability, a pair of indicators should be compared, so the C_{pk} indicator should be calculated as an indicator of the actual capability. The process should be evaluated according to the algorithm shown in Figure 4.

The P_p and P_{pk} coefficient is described as an indicator of process efficiency. It provides information about the process capabilities about the customer's requirements.

$$P_p = \frac{\text{UCL} - \text{LCL}}{6\sigma} \tag{4}$$

$$P_{pk} = \min\left\{\frac{\overline{x} - \text{LCL}}{3\sigma}; \frac{\text{UCL} - \overline{x}}{3\sigma}\right\} \tag{5}$$

$$\text{If} = \sqrt{\frac{\int_{i=1}^{n} (x_i - \grave{x})^2}{n-1}}\sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \overline{x})^2}{n-1}} \tag{6}$$

where:

$\overline{x}$ – average value in the sample
x_i – the result of the ith measurement
n – sample size.

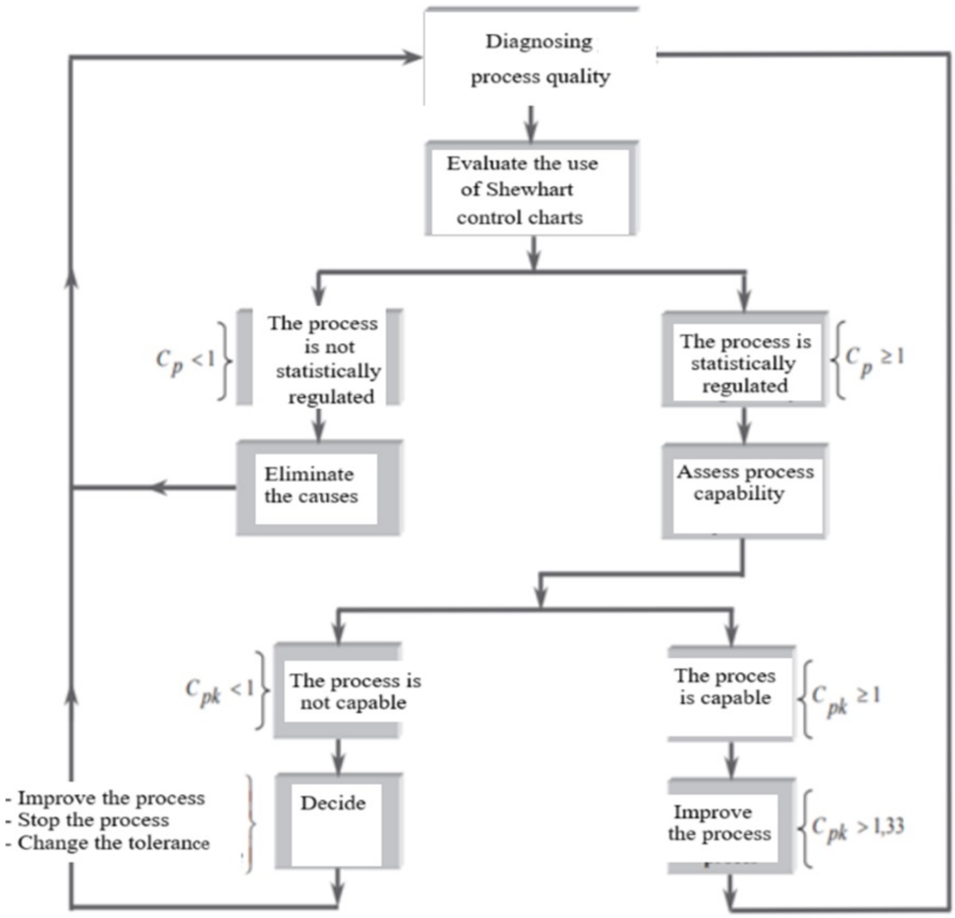

Fig. 4. Algorithm for the strategy for improving the quality capacity of the process

It is important in the study to compare both pairs of coefficients as this gives a true picture of the process. They must be determined at the same time and on the same data. If there are significant differences between the calculated coefficients ($C_p - P_p$ and $C_{pk} - P_{pk}$), this means that there is variability in the process, i.e. the so-called special causes, which are a factor of average instability of the process. If these coefficients are equal ($C_p = P_p$ and $C_{pk} = P_{pk}$), it means that there are no special causes in the process and therefore it is stable from a positional point of view (Niekurzak & Kubińska-Jabcoń, 2021).

To determine the C_p and C_{pk} indices, 5 samples were used. 25 groups of 5 samples were used to determine the long-term index. Both pairs of indicators were compared simultaneously.

The research was carried out according to the adopted algorithm shown in Figure 5.

Results

The quality of the measurement system is an important component that influences the quality of the data obtained. It is not enough to collect and analyze the data, it is also necessary to ensure that the data obtained from the measurements are reliable. To confirm the correctness of the results obtained and to study the variability of the measurement data and their interaction with the overall production process, measurement tests were carried out using the MSA method. The data obtained, presented in Figure 6, show that both methods introduce a measurement variability of more than 30%.

- Caliper – average total variability of the R&R process 44%;
- Depth gauge – average total variability of the R&R process 65%.

The system should be used for smaller tolerance ranges such as 0.3 ∼ 0.5 mm tolerance. In this case, the R&R (total) variability is in the range of 40–50%, which significantly limits its use.

The number of measurement categories is only 4 in one case, and smaller in the other cases, which means that the current measurement system is not able to reliably distinguish different groups of values, bad and good. The depth gauge and caliper method (recommended for thickness measurements) is unreliable because it introduces a large measurement error in terms of tolerance. Existing measurement methods were judged to be inaccurate and imprecise. These errors are due to, among other things, the arrangement of the table, plates, dirt, incorrect positioning of

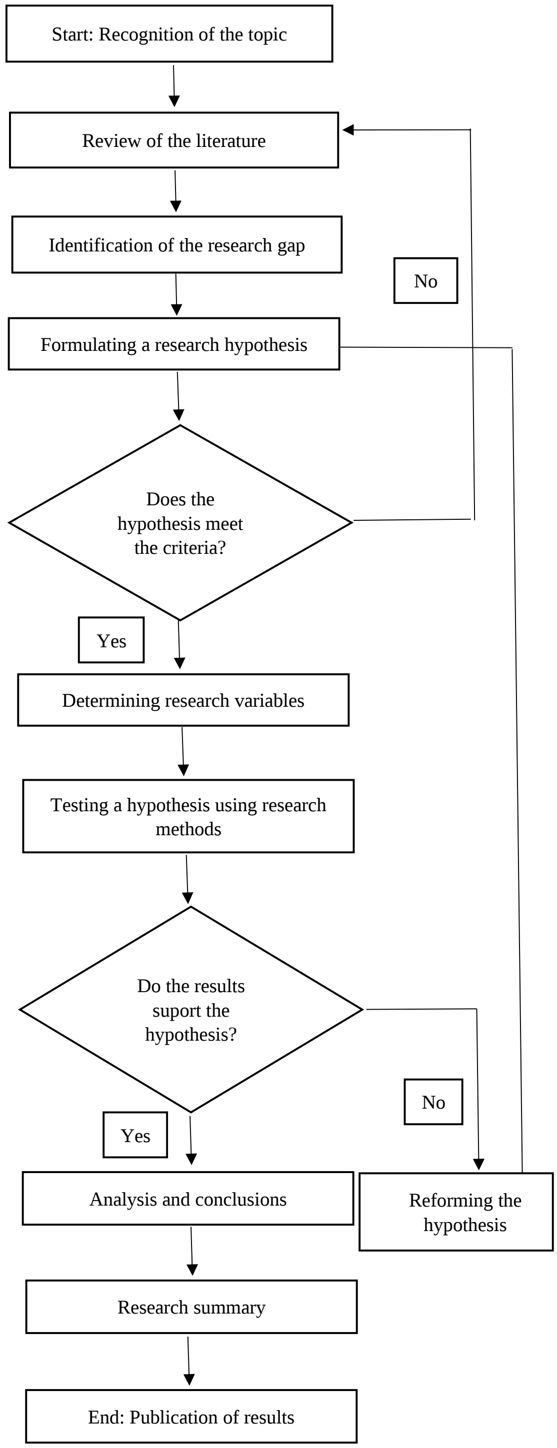

Fig. 5. Flowchart of the research methodology

the instrument on the plate, applied force, incorrect operation, etc. Figure 7 shows a graphical analysis of the ANOVA method for measurement with a caliper, where the variations are divided into four components: the operator's part, the mutual influence of the operator and parts, and the repeatability of the equipment.

R&R results thickness 1	Caliper	Depth gage
Total R&R proces (Study Var)	32%	57%
Total R&R with tolerance (1 mm)	10%	20%
Total R&R Contribution	10%	32%
Number of Distinct Categories	4	2
R&R results thickness 2	Caliper	Depth gage
Total R&R proces (Study Var)	43%	70%
Total R&R with tolerance (1mm)	12%	23%
Total R&R Contribution	18%	49%
Number of Distinct Categories	2	1
R&R results thickness 3	Caliper	Depth gage
Total R&R proces (Study Var)	58%	69%
Total R&R with tolerance (1 mm)	20%	22%
Total R&R Contribution	33%	47%
Number of Distinct Categories	1	1
R&R results thickness 4	Caliper	Depth gage
Total R&R proces (Study Var)	41%	62%
Total R&R with tolerance (1 mm)	13%	20%
Total R&R Contribution	17%	38%
Number of Distinct Categories	3	1
R&R results thickness 5	Caliper	Depth gage
Total R&R proces (Study Var)	70%	83%
Total R&R with tolerance (1 mm)	56%	87%
Total R&R Contribution	50%	69%
Number of Distinct Categories	1	1

Fig. 6. R&R index results

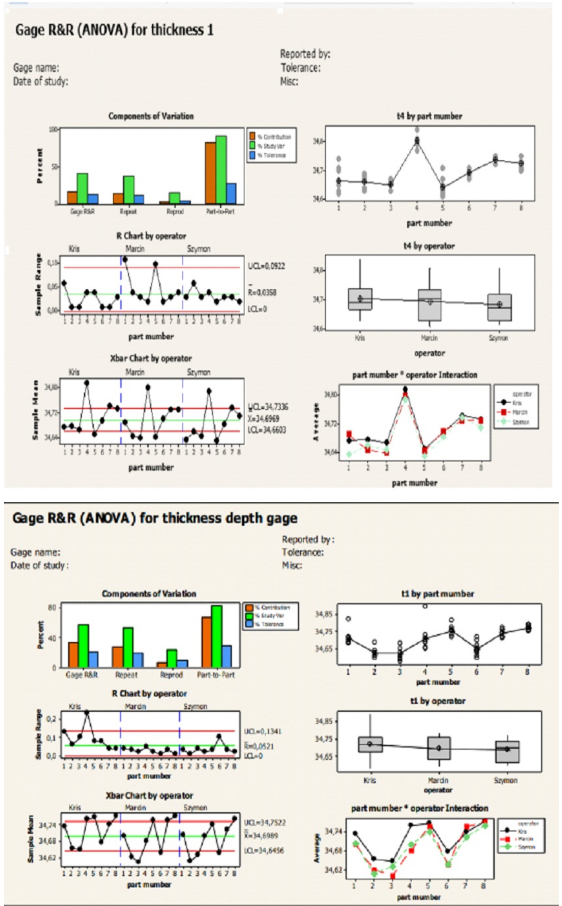

Fig. 7. Graphical analysis of the ANOVA method for caliper measurement

In addition, during the analysis of the graphical data, it was observed that the second operator's measurements using a caliper gauge exceeded the upper control limit and he had a problem with measurement variability, which also affected the quality of the MSA analysis by providing unusual variability, leading to the conclusion that the system itself is very sensitive and operator dependent. This variability could be due to the method of measurement, the position of the gauge, pressure, failure to zero the gauge, contamination or failure to follow a particular standard. This provides the basis for the next analysis, which is to identify and correct any factors affecting the measurement and to ensure corrective action is taken. The third operator has the most stable measurement. It is important that on the "X-bar" graph (which compares the variability and repeatability of measurements), more than 50% of the points are outside the control limits of the measurement system itself. This indicates that the system can detect greater variability between the parts being measured. In Figure 3 you can also see the repeatability limits of the measurement system itself, which are so wide that most of the points (over 50%) are within the limits of this measurement. The result is that the measurement does not discriminate between the variability of the parts being measured, i.e. it does not sufficiently discriminate between parts that represent, as far as possible, the variability of the production process. In addition, when analysing the graphical data, it was observed that the second operator's measurements using a caliper gauge exceeded the upper control limit and he had a problem with measurement variability which also affected the quality of the MSA analysis by providing unusual variability, leading to the conclusion that the system itself is very sensitive and operator dependent. This variability could be due to the method of measurement, gauge position, pressure, failure to zero the gauge, contamination or failure to follow a particular standard. This provides the basis for the next analysis, which is to identify and correct any factors affecting the measurement and ensure that corrective action is taken. The third operator has the most stable measurement. It is important that on the 'X-bar' graph (which compares the variability and repeatability of measurements) more than 50% of the points are outside the control limits of the measurement system itself. This indicates that the system can detect greater variability between the parts being measured. In Figure 3 you can also see the repeatability limits of the measurement system itself, which are so wide that most of the points (over 50%) are within the limits of this measurement. The result is that the measurement does not discriminate between the variability of the parts being measured, i.e. it does not sufficiently discriminate between parts that represent, as far as possible, the variability of the production process. To check the variability of measurements using a camera, 5 boards of the same type were used, two of which were non-compliant products. Each of them was measured three times, generating measurements of all parameters, i.e.: thickness measured in four places, hole position, flatness, width and length. To compare the R&R results, the author presented the results for the thickness and parallelism parameters. The results of thickness measurements are shown in Figure 8, and the results for the parallelism parameter are shown in Figure 9.

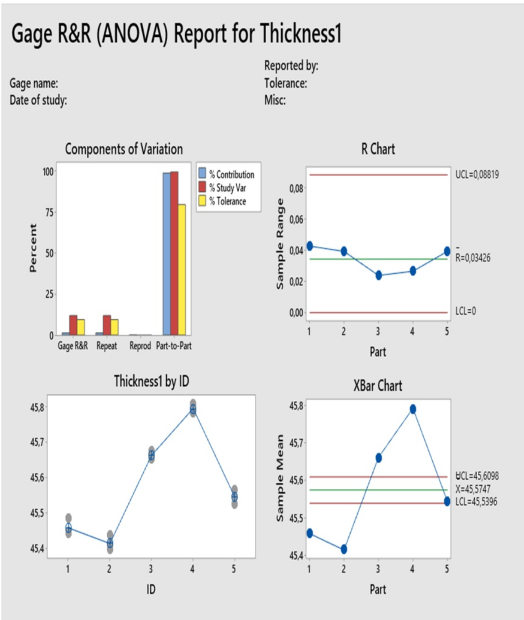

Fig. 8. Analysis of the ANOVA method for measuring product

A good system has a variance that oscillates between the other two. The new system is characterized by the fact that it recognizes the variability between the parts much better, as can be seen from the histogram. The total variability is 11.82. The plots of the repeated measurements of the parts do not differ significantly

WORKSHEET 1

Gage R&R Study - ANOVA Method

* NOTE * There are no operator values, or they are all the same. The operator factor will be omitted from the analysis.

One-Way ANOVA Table

Source	DF	SS	MS	F	P
ID	4	0,269537	0,0673843	102,252	0,000
Repeatability	10	0,006590	0,0006590		
Total	14	0,276127			

α to remove interaction term = 0,05

Gage R&R

Variance Components

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0,0006590	2,88
Repeatability	0,0006590	2,88
Part-To-Part	0,0222418	97,12
Total Variation	0,0229008	100,00

Process tolerance = 0,2

Gage Evaluation

Source	StdDev (SD)	Study Var (5,15 × SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0,025671	0,132206	16,96	66,10
Repeatability	0,025671	0,132206	16,96	66,10
Part-To-Part	0,149137	0,768054	98,55	384,03
Total Variation	0,151330	0,779349	100,00	389,67

Number of Distinct Categories = 8

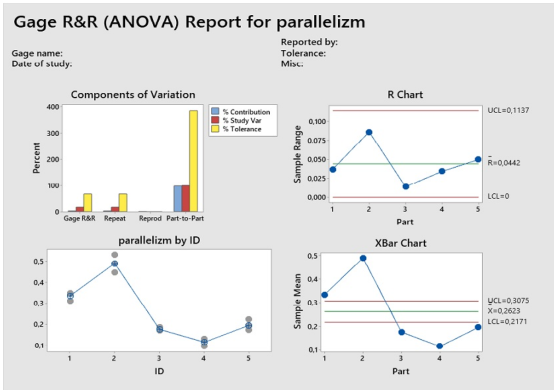

Fig. 9. Results of the ANOVA analysis for the measurement of product parallelism thickness

from each other and the measurement data oscillate around the mean. On this basis, the process was found to be of high quality as it was able to distinguish 11 categories. The system is operator independent and eliminates the human factor.

In the case of parallelism, the results are less satisfactory, but the procedure distinguishes 8 categories and the total variability is 16.96. These results are within the error tolerances of 5 categories. A significant deviation from the average measurements occurs when measuring the third part. The system is also operator independent as it is carried out by an automatic device, which eliminates a source of variability, namely reproducibility. Table 1 gives a summary of the R&R indicators obtained during the tests (Fig. 10) for measurements carried out using a 3D camera.

In Table 1 of the final summary, it can be seen that the R&R index is very high for the length parameter. However, it is not an important criterion because this dimension does not apply to the standard final inspection and the measurement of this parameter is an additional advantage of the analyzed system. Another

Table 1
Summary of R&R indicator results for product parameters

ID	Run	Thickness1	Thickness2	Thickness3	Thickness4	Parallelizm	Flatness scan mean	Flatness scan RMS	Flatness surf mean	Flatness surf RMS	Diameter	Position X	Position Y1	Position Y2	Width	Length
1	1	45.4464	45.3948	45.7062	45.6595	0.3114	0.1767	0.0405	0.0656	0.0152	80.0241	120.0769	74.7636	75.3257	230.1255	441.2272
1	2	45.4431	45.3698	45.715	45.6437	0.3452	0.1842	0.0394	0.0649	0.0150	80.0017	120.1706	74.7599	75.3416	230.1191	441.2993
1	3	45.4857	45.4043	45.7526	45.7158	0.3483	0.1833	0.0408	0.0655	0.0152	79.9972	120.2421	74.7558	75.3405	230.1056	441.2658
2	1	45.4098	45.6955	45.7195	45.7227	0.4460	0.1997	0.0436	0.0620	0.0143	79.890	119.7388	74.9419	75.4670	230.2863	441.4025
2	2	45.4363	45.7074	45.8092	45.8814	0.4882	0.1999	0.0448	0.0623	0.0143	79.8928	119.8282	74.9231	75.4782	230.2722	441.5663
2	3	45.3971	45.7251	45.7752	45.8400	0.5322	0.1970	0.0432	0.0624	0.0144	79.8522	119.8651	74.928	75.4944	230.2527	441.5059
3	1	45.6527	45.7035	45.7017	45.6007	0.1715	0.1943	0.0452	0.06	0.0138	79.8737	119.7665	75.0257	75.468	230.3544	441.4261
3	2	45.6765	45.7158	45.5938	45.6828	0.1725	0.1966	0.0466	0.0594	0.0138	79.8921	119.6705	75.031	75.4438	230.3624	441.3152
3	3	45.6574	45.7265	45.6884	45.6792	0.1855	0.1928	0.0446	0.0602	0.0139	79.8476	119.8364	75.0282	75.4794	230.3482	441.3933
4	1	45.7908	45.8864	45.851	45.9268	0.0956	0.1767	0.0327	0.0616	0.0142	79.9377	120.031	74.5888	75.5811	230.1099	441.3819
4	2	45.7819	45.904	45.8621	45.9334	0.1221	0.181	0.0331	0.0614	0.0141	79.9267	120.0594	74.6058	75.5919	230.125	441.6940
4	3	45.8084	45.9053	45.9187	45.9745	0.1298	0.1708	0.0315	0.0609	0.014	79.9138	120.1072	74.5734	75.6058	230.0946	441.3568
5	1	45.5248	45.508	45.4244	45.3514	0.1734	0.136	0.0322	0.0738	0.017	80.0793	120.3618	75.302	74.7917	230.1729	441.3527
5	2	45.564	45.5766	45.3539	45.4329	0.223	0.129	0.0305	0.0726	0.0167	80.1201	120.2808	75.2922	74.7485	230.159	441.3104
5	3	45.5456	45.5418	45.3552	45.3991	0.1904	0.1329	0.0315	0.0737	0.017	80.0938	120.2906	75.2988	74.7743	230.1648	441.2384
R&R %		11	10	22	20	17	13	13	8	9	19	27	3	5	11	59
R&R tol %		9.5	10	21	21	66	3.6	1	5	1	4	17	2	4	3	10
Contribution %		1.4	1	5	4	2.9	1.8	1.8	0.5	0.7	3.8	7	0.1	0.2	1.3	35
NDS		11	13	6	6	8	10	10	17	15	7	4	42	29	12	1
3D avg																
1		45.458	45.390	45.725	45.673	0.335	nok				80.008	120.163	74.760	75.336	230.117	441.264
2		45.414	45.709	45.768	45.831	0.489	nok				79.878	119.811	74.931	75.480	230.270	441.492
3		45.662	45.715	45.661	45.654	0.177					79.871	119.758	75.028	75.464	230.355	441.378
4		45.794	45.899	45.877	45.945	0.116					79.926	120.066	74.589	75.593	230.110	441.403
5		45.545	45.542	45.378	45.394	0.196					80.098	120.311	75.298	74.772	230.166	441.301
caliper																
1		45.49	45.37	45.84	45.71	0.47		0.15		0.03	79.89	121.3	74.85	75.39	230.18	441.4
Delta 3D vs caliper		0.0316	–0.0197	0.1154	0.037	0.1351					0.118	–1.137	–0.090	–0.054	–0.063	–0.136
2		45.48	45.67	45.87	45.85	0.39		0.15		0.02	79.85	120.3	75.05	75.69	230.32	441.1
Delta 3D vs caliper		0.0656	–0.0394	0.1021	0.0187	–0.0988					–0.028	0.489	0.119	0.210	0.050	–0.392
3		45.7	45.63	45.76	45.66	0.13		0.2		0.02	79.84	118.9	75.18	75.62	230.41	438.1
Delta 3D vs caliper		0.0378	–0.0853	0.0987	0.0058	–0.046					–0.031	–0.858	0.152	0.156	0.055	–3.278
4		45.81	45.82	45.97	45.97	0.16		0.15		0.02	79.77	120	74.73	75.71	230.47	441.1
Delta 3D vs caliper		0.0163	–0.0786	0.0928	0.0251	0.0442					–0.156	–0.066	0.141	0.117	0.360	–0.303
5		45.58	45.47	45.41	45.4	0.18		0.2		0.02	79.91	120.9	75.58	74.96	230.23	441.4
Delta 3D vs caliper		0.0352	–0.0722	0.0322	0.00554	–0.015					–0.188	0.589	0.282	0.188	0.064	0.099

Fig. 10. A production belt directing the plates into the camera

high R&R indicator is the X dimension measurement of 27%, but it is within the assumptions of the method for R&R of less than 30% and can be accepted. The average process variability for thickness measurement with a caliper was 44%, for the 3D system the highest rate for thickness was 22%. The parallelism measurement was also stabilized with a result of 17%, compared to 70% for the traditional caliper measurement.

The implementation of a new measurement system helped to increase the accuracy of the measurements. The process capacity was therefore calculated. The results of the calculation are presented in Figures 11–13 using the Minitab application.

The measured data is normal. This was also illustrated in a graph showing the normal distribution of the analyzed data. The thickness of the tested product is ideal if its value is equal to 45.5. The determined lower limit of the product is 45 and the upper limit is 46. The standard deviation is estimated to be 0.1475. The process mean is significantly different from the target.

The Xbar chart shows that most of the measurement groups are within specification. However, the process is not running as planned because not all the measurement groups are centered on the specification limits. One group of points (the average from one batch) is outside the upper limit of the control limits, which in this case indicates instability, also known as atypical (special) variability. The short and long-term capacity coefficients are $C_p = 1.19$, $C_{pk} = 1.08$, $P_p = 1.13$ and $P_{pk} = 1.03$. If $C_p > 1$ and $C_{pk} > 1$, the process is considered to be qualitatively capable.

When interpreting the process capability results, it is recommended that the C_p, C_{pk} and P_p, P_{pk} coefficients are determined from the same data at the same time and then compared. No significant differences were found between the coefficients ($C_p - P_p$ and $C_{pk} - P_{pk}$),

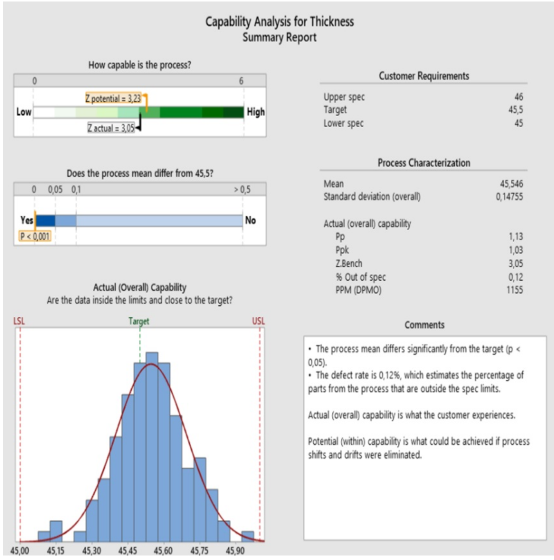

Fig. 11. Process capability analysis – Part 1

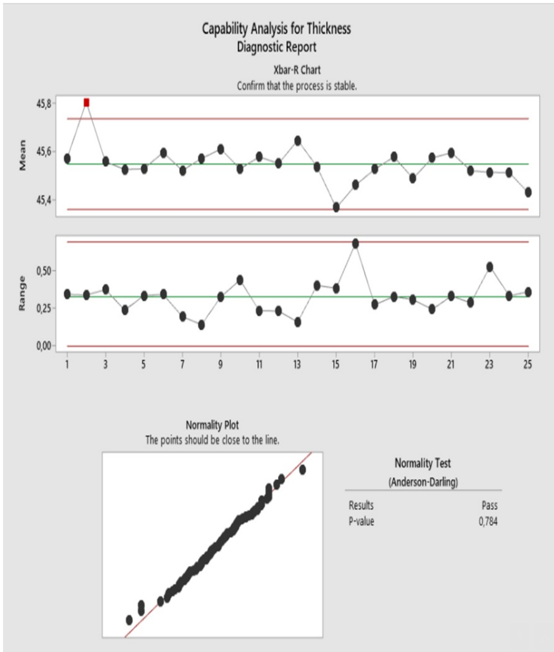

Fig. 12. Dispersion of measurement groups relative to tolerance

which means that there are mainly typical variations in the process, indicating that the process is stable. It was found that instabilities can occur in the process, as evidenced by one of the subgroups. The potential process capability (in batches) of C_p – 1.19 suggests that the company will achieve this value if it identifies and eliminates batch-to-batch variability. The data shows that the potential percentage of product out of specification is at the level of 0.12%, with a tendency to exceed the upper tolerance, making the product

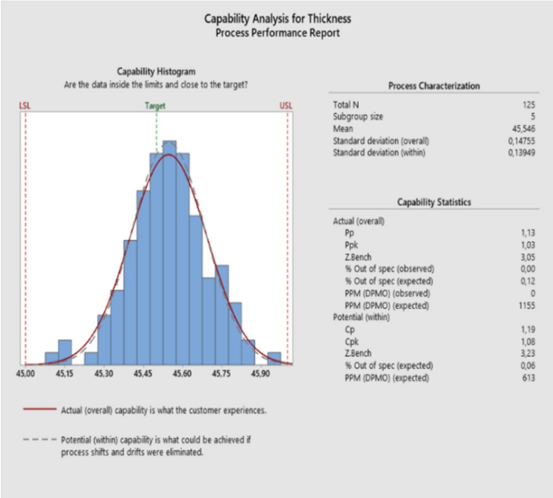

Fig. 13. Process capability analysis – Part 2

out of specification. DPMO index = 1.155 parts per million. Based on the hypothesis test assumed by the analysis programme:

H_0 – (null hypothesis) = the average value of the thickness of the products is equal to the target,

H_a – (alternative hypothesis) = average the thickness value of the products is not equal to the target.

This can be determined based on the analysis $p < 0.05$, which means that it can be concluded with 95% confidence that the average of the products is statistically different from the target for the process. This deviation is accepted by the customer but forms the basis for correcting the process by working on the centering of the product processing process.

Before implementing the system, an FMEA analysis was carried out to predict undesirable events. Table 2 shows the FMEA analysis, which highlights the main elements of the measurement system and distinguishes potential non-conformances and their possible causes. The PRN index was calculated to assess the risk and then to determine preventive actions.

Table 2
Production belt directing the plates into the camera

Proces step	Failure Mode Proces	Effect(s) Product	Cause(s)	Actual risk					Action/Investigation
				S	O	SxO	D	RPN	
Transferring the disc to the tray	Disc placed on the tray contrary to the laser indications	The plate will fall	Operator's inattention	3	5	15	1	15	
			Poorly written instructions	3	1	3	1	3	
			Laser shift	3	1	3	1	3	
		Was not read	QR code invisible to the reader	3	5	15	1	15	
		Board blocking at input/output	Low precision of positioning	5	3	15	3	45	
	Disc placed on the upside-down tray	The plate will fall	Operator's inattention	7	3	21	5	105	Stabilized standard of plate placement for product groups
			Poorly defined standard	7	1	7	5	35	
			Untrained operator	7	5	35	5	175	Instruction/deposit standard
	The board is laid snd not sanded	Plate rejected	Operator's inattention	3	1	3	1	3	
			OEE low	5	3	15	1	15	
			Clogged station exits	5	7	35	1	35	Develop instructions
	Lack of space	Stacking on the feeder	Stopped tunnel furnace	5	9	45	1	45	Standard positioning of plates/the furnance cannot be turned off except in case of failure/continuity of operation
			Machine cycle not adapted to line capacity	7	3	21	1	21	

Table 2 continued on the next page

Table 2 continued from the previous page

Proces step	Failure Mode Proces	Effect(s) Product	Cause(s)	Actual risk					Action/Investigation
				S	O	SxO	D	RPN	
Transffering the disc to the tray	Location of the dirty surface plate	Plate read as NOK	Water with sludge	5	7	35	1	35	Establishing a standard for washing plates
			No water cleaning	3	3	9	1	9	
			Not enough water	7	7	49	1	49	
		Tape dirty	Build-up on the tapes	5	7	35	1	35	Adapt the water connection to grinders
	Location of the disc with a dirty QR code	The disc will be rejected	Water with sludge	5	7	35	1	35	Develop a new cleaning standard
			No water cleaning	3	3	9	1	9	Standard for cleaning and confirming the readability of the QR code
			Not enough water	7	7	49	1	49	Information in the manual
			Build-up on the tapes	5	7	35	1	35	
	Plate arrangement without QR code	The disc will be rejected	Faulty laser	7	5	35	1	35	Confirmation of code readability
	Placing a disc with a damage QR code		Mechanical damage	7	7	49	1	49	Code corruption analysis
			Laser error	7	5	35	1	35	Two lasers can work independently
	Capture of body parts	Injury	Being pulled through the tape	9	3	27	1	27	
			Loose parts	9	3	27	1	27	
	Entry of joined slabs into the station	Plate fall	Failure of te transporter system	5	3	15	1	15	
Air curtain	Improper drainage	Under-drying	Too weak blowing/nozzle clogging	5	3	15	1	15	
	When the product is dirty	Accumulation of dirt in one place of the palte	Not rinsing the disc	5	1	5	1	5	
	Curtain height incorrectly set	Plate set too high	Reference room	3	3	9	1	9	
		Plate set too low		5	3	15	1	15	
Reading QR	The scanner in dirty	No reading	Dust/splashes	5	3	15	1	15	
	Damaged QR reader		Mechanical/electric	5	3	15	1	15	
Disc without QR code	To many disc read as QR NOK	A lot of disc on the conveyor	Corrupted codes. No codes, reader not working, etc.	7	7	49	1	49	Checking the sensors
		Blocking the operation of the station		7	9	63	1	63	Manual measurement
		Plates mayfall off the conveyor	Queue/pressing	7	7	49	1	49	Checking the sensors
	Squeezing/ impacting limbs	Limb injury	Queue/pushing/ tilting angle	9	7	63	1	63	Instructions for the operator on removing the plates
	Plate falling from the conveyor	Disc damage		5	5	25	1	25	
Lifting/ hoisting	Fall of the plate from the conveyor elevator	Disc damage	Incorrectly set board/sensor failure	9	5	45	1	45	Information for the operator, blocking of transporter stations
		Equipement damage							
		Blocking the transporter							
		Possible injuries when removing the plate							

Table 2 continued on the next page

Table 2 continued from the previous page

Proces step	Failure Mode Proces	Effect(s) Product	Cause(s)	Actual risk					Action/Investigation
				S	O	SxO	D	RPN	
Measurement	Malfunction of the measurement system	Unique measurement	Decalibrating the system	7	7	49	3	147	Analysis of the camera program, procedurę for checking the correctness of measurement
		Good albums as NOK							
		Bad records as OK	Automation system error						
		No report							
	Measurement time too long	System suspension	Measurement/ automation system error	7	7	49	3	147	
		Lack of requirement performance							Emergency procedure
		STOP station							
Removal of NOK plates	Squeezing/ impacting limbs	Injury	Queue/pressing	7	7	49	3	147	Emergency procedure
	Plate falling from the conveyor	Disc damage		9	7	63	1	63	
Selection of discs	Too many plates read as NOK	Many NOK albums	Measurement/ automation system error	7	7	49	3	147	Re-measurement
		Blocking the operation of the station		5	7	35	1	35	Develop an operating manual
	Squeezing/ impacting limbs	STOP station							
		Injury							
Turntable	Incorrect position of the turntable	No transfer of the board to the drying line	Measurement/ automation system error	9	7	63	1	63	Develop an operating manual
	Blocking of the turntable by the transporter	Mechanical damage	Stuck discs	7	7	49	1	49	Failure/failure procedure

Discussion

The main quality criterion of the finished products is their appropriate dimensional tolerance. To this end, analyses of the measurement systems (using a caliper and a depth gauge) of the ladle gate valve production process were carried out. In addition, a study was carried out on the implementation of a modern measurement system to reduce products that do not comply with standards and technical specifications (Haverkamp & Beauducel, 2017). Under this system, you should expect:

- The measurement process should take less than 30 seconds;
- Full cycle optimization;
- Minimize errors, a required measurement accuracy of 0.1 mm;
- The system will be an integral part of the whole process.

Automatic generation of reports with OK identification and visualization of a specific tested object:

- Data archiving options;
- The possibility of checking the quality of calibration;
- Product identification using a QR code reader;
- Resistance to specific factors such as light, vibration, dust, temperature and humidity.

The most important elements in the interpretation of the measurement analysis are:

- The Source column indicates the cause of the variation;
- The DF column indicates the degree of freedom associated with the source;
- The SS column shows the deviation from the source mean;
- The MS column is the sum of the squares divided by the degrees of freedom.

Defines the so-called linearity:

- The F column is calculated to determine the significance statistic of the source value;
- The P column (p-value) is the most important value. If it is greater than the assumed significance level, it means that the differences between the operators' measurements are not critical;
- The most important indicator is %Study Var(%SV), which means the variability for the whole R&R test;
- The indicator %Tolerance(SV/Toler) shows the variability concerning the specified tolerances.

The number of Distinct Categories indicates the ability of the R&R test to distinguish individual categories. A process in which it is not possible to distinguish at least five categories is described as having a low process quality.

The results provide information on the variability of the data:

1. The histogram shows the components of the variability. Each group represents a different source of variability. The graph consists of three bars representing the contribution of tolerance and variance. A good system will have a variance that fluctuates between the other two.
2. The R chart is a control chart that shows the consistency of the results of individual operators. It consists of plotted points which, for each operator, represent the difference between the largest and smallest measurements of each part. There are also upper and lower control limits and a median line which is the average of all subgroups. If the operators measure consistently, the ranges will be small and the points will be within the control limits.
3. The Xbar plot compares the deviation of measurements against the part by analyzing the repeatability components. The Xbar graph consists of plotted points representing the average measurement of each part for each operator. The graph is visually similar to the previous graph but shows different data. It also shows the control limits (UCL and LCL) and a center line which is the overall average of all part measurements taken by the operators.
4. The graph shows the interaction between the part and the operator. All measurements in the study are arranged by part. This location of multiple measurements for each part allows you to visualize measurement differences.
5. The box plot by the operator helps to determine whether measurements and variability are consistent between operators. The black circles represent the average and the lines connect them. If the operators measure identically, this line is parallel to the X-axis.
6. Operator and part interaction graph. Shows the average measurements taken by each operator for each part. Each line combines the averages for a single operator. Ideally, the lines will be virtually identical, which means that the operators are measuring identically, i.e. they are reproducible.

The FMEA analysis presented shows that the most critical threats include operator error due to ignorance or error. This indicates the importance of the human factor in the measurement process. To eliminate this risk, the plates were divided into three groups and a standard was adopted for placing the plates on a tape. In addition, lines were marked on the tape to indicate the position of the plate on the tape, determined by the length of the plate. In addition, staff were trained and all information was included in additional job documents. Another high-risk element was the problem of reading the QR codes on the discs, due to the lack of the code or its illegibility. Without a readable code, the system is unable to analyze a given product. For this reason, the station has been equipped with a QR code printer, which allows the disc that is rejected because it is unreadable to be taped and then placed back on the conveyor. The most common concern was the error measurement resulting directly from the system (Niekurzak & Mikulik, 2021). This factor could not be eliminated, as it is not possible to directly predict the cause and time of occurrence, but as part of the control and preventive measures, several actions were implemented, such as:

1. Creation of two reference boards, one conforming and one not conforming to the assumed specifications. After a test measurement, these references indicate whether the measurement is accurate, distinguishes dimensions correctly and classifies them appropriately. The boards were measured in the metrology laboratory and the accuracy of the system was assessed based on these measurements.
2. Instructions have been developed on how to use the measuring station and how to solve problems independently, such as recommended actions due to missing files with measurement results, incorrect dimensions or the generation of poor-quality scans.

In summary, the analysis made it possible to predict potential non-conformities and their impact on the measurement process. The quality of the process and its reliability were improved. A contingency plan was established in case of non-conformity. Preventive actions were planned and preventive control measures were implemented. Thanks to the use of FMEA analysis, potential failures were identified that should be eliminated first because they threaten the correct operation of the process. The necessary preventive actions and a response plan to be used in the event of an error have also been introduced.

Conclusions

The methodology presented for analyzing measurement systems can and should be used in all areas of measurement. Of course, the scope of the analysis must be appropriate for the measurement systems used. At present, the technical implementation of MSA analyses does not pose any major problems, not to mention the corrective actions to be taken in case of negative results (disqualification of measurement systems). People performing analyses have access to ready-made forms, examples, spreadsheets and specialized commercial software. Many people responsible for the selection and qualification of measuring instruments have become convinced of the practical value of the analyses performed, and are more likely to encounter organizational rather than substantive obstacles when trying to cover subsequent measuring systems with MSA tests. Quality assurance requires funding. MSA analysis, which fits perfectly into the philosophy of quality assurance and improvement, obviously requires resources: time of qualified personnel to perform analysis and corrective actions, time of operators/controllers to participate in test measurements, and time to remove the tested equipment from the production process. The cost of obtaining standards, sample preparation and the cost of any supporting software appear to be the least important components of the cost of analyzing the capabilities of MSA measurement systems. The problem of MSA management has not yet been developed into "good practice", so a good understanding of the expected effects and limitations, as well as the resources required, is crucial, especially in companies that perform capability testing of measurement systems, often solely due to standard or customer requirements.

Based on the analysis of the production process and the quality controls carried out, the following conclusions were drawn:

1. The FMEA study has protected the company against undesirable events. The main problems that occur during the operation of the system are software-related problems that cannot be eliminated.
2. Thanks to the MSA study, it was found that the measurement introduced with the 3D system significantly reduces process variability by eliminating one of the variability factors, i.e. the human being. The 3D camera collects more accurate data, so the calculation of process capacity was also more accurate. The results obtained prompt action to improve stability, but the current state is acceptable to the customer.
3. The great advantage of the system is that a large number of accurate measurements can be obtained in a short time, reducing the measurement cycle. The system speeds up the process and reduces the number of incorrect data, which helps to reduce the number of non-conforming products. It quickly creates and stores databases of measurements, allowing data to be analyzed more accurately and more frequently without special preparation. The database makes it possible to search and provide the customer with a report on a specific board from measurements taken over a very long period. The company has also set itself apart from others by providing customers with measurement results in graphical form. In addition, 100% of the manufactured products are measured, but measurements at other finishing stations are reduced and final inspection measurements are excluded. As a result, products are released based on the data generated by the system. In addition, box release time has been improved by excluding random measurements of boards from boxes and storing the received data in base files.

Summarizing the obtained results, it should be noted that visual inspection can significantly influence the improvement of the production process, because thanks to the appropriate analysis of quality control results, e.g. analysis of the structure of non-conformities and their causes, then determination of appropriate corrective actions and continuous monitoring of the situation after the implemented corrective actions, you can significantly reduce or even prevent the occurrence of quality problems in the future. Visual inspection can add significant value to the process, as demonstrated in this article. It should be emphasized that for this to be the case, the results of the visual inspection must be reliable, without conformity assessment errors, because these errors, in the form of incorrect classification of the product in the OK or nOK category, can contribute to the deterioration of the efficiency of the production process.

The efficiency of the measurement system has been significantly improved from 78% to 98%. This is due to the possibility of using a 3D camera sensor based on parallel technology and simultaneous image analysis for IVC-3D on each of the 1024 columns of the matrix. Thanks to this technology, details can be distinguished with a resolution of 0.015 mm in a field of view of 60 mm. As a result, even small surface, edge or position defects are perfectly visible and can be automatically detected. This technology allows you to eliminate almost 100% of production defects at the initial stage of non-destructive testing. The use of this technology also makes it possible to limit stoppages practically only to mandatory service work. Thanks to this solution, finished products are of higher quality and production costs due to unplanned downtime and production defects are reduced to a minimum.

Further research should present solutions aimed at implementing full automation to run production at the highest quality level using the principle of lean production. Simulation tests can be carried out to confirm the implementation of changes, for example using FlexSim software in combination with the FloWorks module. The benefits of this programme allow you to build complete models of continuous processes and perform advanced optimization on them.

Although the considerations presented are not exhaustive, they should draw attention to the modelling and optimization of production processes in a real production environment as part of the idea of Industry 4.0. There is no doubt that increasing productivity and reducing production costs is a significant challenge, which cannot be successfully achieved without breakthrough changes in production paradigms and the underlying technologies and applications. According to the authors, appropriate tools, such as those discussed in this article, have the potential to play a significant role in the evolution from Industry 4.0 to Industry. 5.0. In key areas such as simulation, systems integration, autonomous systems, cloud computing, augmented reality, big data and data analytics.

References

Antosz, K. (2012). Application of the R&R method to the analysis of selected measurement systems. *Technology and automation of assembly* 3, 57–61. [in Polish]

Binczyk, B., Świsulski, D. (2012). Scanning 3D objects using a laser and camera. *Scientific Journals of the Faculty of Electrical Engineering and Automation of the Gdańsk University of Technology*, 31, 35–39. [in Polish]

Bosley, T. (2019). *Comparative power of the Friedman, Neave and Worthington match, Skillings-Mack, trimmed means repeated measures ANOVA and bootstrap trimmed means repeated measures ANOVA tests* [Doctoral dissertation, Wayne State University].

Haverkamp, N.,,Beauducel, A. (2017). Violation of the sphericity assumption and its effect on Type-I error rates in repeated measures ANOVA and multi-level linear models (MLM). *Frontiers in Psychology, 8*, 1841. DOI: 10.3389/fpsyg.2017.01841

Haverkamp, N., Beauducel, A. (2019). Differences of Type I error rates for ANOVA and Multilevel-Linear-Models using SAS and SPSS for repeated measures designs. *Meta-Psychology, 3*, Article MP.2018.898.

Islam, M., Chowdhury, R. (2017). *Analysis of repeated measures data. Springer*. DOI: 1.1007/978-981-10-3794-8

Kosiorek, D. (2013). Quality in the theory and practice of organizational management. *Management and Finance*, 1/1, 339–358.

Kowalik, K. (2018). FMEA method in quality management theory and practice. *Engineering Knowledge Archive*, 2/3, 23–25.

Król, J. (2020). *SPC/MSA, Statistical Process Control and Analysis*. Luquam, Cracow.

Maurissen, J., Vidmar, T. (2017). Repeated-measure analyses: Which one? A survey of statistical models and recommendations for reporting. *Neurotoxicology and Teratology, 59*, 78–84.

Mubashar Arshad M., et.al. (2022). Scrutinization of slip due to lateral velocity on the dynamics of engine oil conveying cupric and alumina nanoparticles subject to Coriolis force. *Mathematical Problems in Engineering*, 1, 2526951.

Mikulik, J., Niekurzak, M. (2023). Impact of a photovoltaic installation on economic efficiency on the example of a company with high energy consumption. Scientific Papers of Silesian University of Technology. *Organization and Management*, 169, 521–540.

Niekurzak, M., Lewicki, W., Coban, H.H, Brelik, A. (2023). Conceptual Design of a Semi-Automatic Process Line for Recycling Photovoltaic Panels as a Way to Ecological Sustainable Production. *Sustainability*, 15(3), 2822. DOI: 10.3390/su15032822

Niekurzak, M., Mikulik, J. (2021). Modelling of Energy Consumption and Reduction of Pollutant Emissions in a Walking Beam Furnace Using the Expert Method—Case Study. *Energies* 2021, 14, 8099.

Niekurzak, M., Kubińska-Jabcoń, E. (2021). Production line modelling by the Industry 4.0 concept as an element of process management in the iron and steel industry. *Management and Production Engineering Review*, 12(4), 3–12.

Ostrowska, K. (2004). Quality management system in accordance with ISO 9001:2000 requirements – this is what you need to know, in ISO 9001. An effective way to obtain a quality certificate, edited by Eckhard Kreier, Jacek Łuczak, 1/1, 1, Forum Publishing House Sp. z o.o., Poznan.

Pająk, E., Diering, M. (2010). Ongoing evaluation of the usefulness of measurement systems in the manufacturing process. *Part I: "Enterprise Management" methodology*, 1, 2–13.

Pietras, E. (2017). Assumptions of the quality management system on the example of an enterprise. *Organization and Management*, 12, 1765–1769.

Roszak, M.T. (2014). *Quality management in engineering practice,* Library, 1/31, 1-150. [in Polish]

Rusecki, A. (2018). Practical application of the FMEA method on the example of pulley production in a selected company. *Quality Production Improvement*, 1(8), 7–18. [in Polish]

Skotnicka-Zasadzień, B. (2012). Analysis of the effectiveness of using the FMEA method in a small industrial enterprise. *Production Systems Management Support*, 2(2), 142–153. [in Polish]

Stadnicka, D., Jastrzębski, P. (2015). Application of the FMEA method to improve the mixer design. *Technology and Automation of Assembly*, 4, 30–34. [in Polish]

Stefanów, P. (2013). Analiza zdolności procesu. *Foil Oeconomica Cracoviensia*, 54, 117–132. [in Polish]

Szerszunowicz, M. (2013). Capacity analysis of a process with dependent characteristics. *Economic Studies*,152, 153–161. [in Polish]

Terenowski, H. (2010). Estimation of Measurement Uncertainty. *Weapons Technology Problems*, 39/115, 77–84.

Ullah, I., Hussain, I., Rehman, K., Wróblewski, P., Lewicki, W., Kavin, B.P. (2022). Exploiting the Moth–Flame Optimization Algorithm for Optimal Load Management of the University Campus: A Viable Approach in the Academia Sector. *Energies*, *15*, 3741. DOI: 10.3390/en15103741

Wróblewski, P., Niekurzak, M. (2022). Assessment of the possibility of using various types of renewable energy sources installations in single-family buildings as part of saving final energy consumption in Polish conditions. *Energies*, 15,1329.

Wróblewski, P., Niekurzak, M., Kachel, S. (2023). Experimental studies of welded joints in structures subject to high-impact vibrations using destructive and non-destructive methods. *Materials*, 16(5), 1886.

Wróblewski P. (2023). Reduction of friction energy in a piston combustion engine for hydrophobic and hydrophilic multilayer nanocoatings surrounded by soot. *Energy*, 271, 126974. DOI: 10.1016/j.energy.2023.126974

Wrona, M. (2014). Structured light technique in the process of documenting the scene of a road accident. *Logistics*, 6, 11394–11400. [in Polish]

Wyrębek H. (2012). The importance of the FMEA method in quality management in enterprises. *Scientific Journals of the University of Natural Sciences and Humanities*, Siedlce, 92, 151–165. [in Polish]

Yu J, Qiao C., Zhang S., Liu Z., Wróblewski P. (2023). Tribological properties of laser-cladded Fe-based amorphous composite coatings under dry and lubricated sliding. *Optics & Laser Technology*, 166, 109583. DOI: 10.1016/j.optlastec.2023.109583