Technologia i Automatyzacja Montażu

Volume 124, Issue 2/2024, Pages 18-28
https://doi.org/10.7862/tiam.2024.2.3

Original Research

CLASSIFICATION GRAPH OF POKA-YOKE TECHNIQUES FOR INDUSTRIAL APPLICATIONS: ASSEMBLY PROCESS CASE STUDIES EFFECTIVENESS EVALUATION

GRAF KLASYFIKACJI TECHNIK POKA-YOKE DO ZASTOSOWAŃ PRZEMYSŁOWYCH: OCENA EFEKTYWNOŚCI STUDIÓW PRZYPADKÓW DLA PROCESU MONTAŻU

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Abstract

It is widely acknowledged that the expenses associated with substandard quality constitute a significant portion of a company's overall costs. Consequently, organizations adopt quality management systems and implement corrective and preventive measures to reduce these expenses. Within these implementations, Poka-Yoke (P-Y) techniques are notably prominent. Theoretically, these techniques are designed to prevent mistakes that lead to costs, especially quality-related costs associated with nonconforming products. This study proposes a classification graph of P-Y techniques, which serves as a tool for evaluating the effectiveness of these techniques in preventing errors that lead to product nonconformities, machine failures, operator injuries, or environmental threats. The Classification Graph was developed based on a study of 139 P-Y solutions implemented in 24 companies operating in the automotive, aviation, and metal processing industries. The value of this graph lies in its ability to easily evaluate and prioritize different P-Y techniques, aiding in the design of new techniques and the improvement of existing ones to enhance the reliability of production systems.

Keywords: mistake proofing, Poka-Yoke, effectiveness, collaborative robots, assembly

Streszczenie

Powszechnie uznaje się, że wydatki związane z jakością poniżej standardu stanowią znaczną część ogólnych kosztów firmy. W związku z tym organizacje przyjmują systemy zarządzania jakością i wdrażają środki korygujące i zapobiegawcze w celu zmniejszenia tych wydatków. W ramach tych wdrożeń techniki Poka-Yoke (P-Y) są szczególnie ważne. Teoretycznie techniki te mają na celu zapobieganie błędom, które prowadzą do kosztów, zwłaszcza kosztów związanych z wyrobami niezgodnymi. W niniejszym badaniu zaproponowano wykres klasyfikacji technik P-Y, który służy jako narzędzie do oceny skuteczności tych technik w zapobieganiu błędom, które prowadzą do niezgodności wyrobów, awarii maszyn, obrażeń operatorów lub zagrożeń dla środowiska. Graf klasyfikacji został opracowany na podstawie badania 139 rozwiązań P-Y wdrożonych w 24 firmach działających w branży motoryzacyjnej, lotniczej i obróbki metali. Wartość tego wykresu polega na jego zdolności do łatwej oceny i ustalania priorytetów różnych technik P-Y, co pomaga w projektowaniu nowych technik i ulepszaniu istniejących w celu zwiększenia niezawodności systemów produkcyjnych.

Słowa kluczowe: zabezpieczenie przed błędami, Poka-Yoke, efektywność, roboty współpracujące, montaż

1. Introduction

In order to ensure that a company remains on the market, it must be competitive in terms of product quality and selling price. That is why, it has to find strategies to reduce costs while preserving the level of quality expected by their customers.

It has been noticed that a considerable part of companies' costs are costs of poor quality (Tkaczyk and Jagła, 2001). For this reason, the companies began to undertake the activities concerning cost minimization (Yoo et al., 2012). To find a source cause of the quality problems the companies undertake various actions. They use simple quality management tools, such as Ishikawa diagram (Kumar et al., 2009) or methods such as FMEA (Pinosova and Andrejiova, 2023; Xiuxu, 2011; Sellappan and Palanikumar, 2013) to find possibilities for improvements. Additionally, more and more popular is six sigma methodology, which is applicable for more difficult quality problems (Valles et al., 2009; Yusuf and Halim, 2023). The result of these analyses is an information about weak points in production system, where any corrective and preventive actions should be undertaken.

However, it is not solely about enhancing control processes to prevent nonconforming products from reaching customers. First of all, it is about undertaking preventive actions to prevent the production of nonconforming products, for example by using control charts (Chen et al., 2011; Dahari et al., 2025). That is why, different kinds of solutions, which can prevent nonconformities or which can significantly minimize their number, are implemented. These solutions are called Poka-Yoke (fail safe) and they are implemented not only in the production companies (Martinelli et al., 2022; Kozikowski et al., 2022; Trojanowska et al., 2023) but also in services (de Saint Maurice et al., 2011; Amaral et al., 2023). Literature propose not only physical but also digital Poka-Yoke techniques (Rahardjo et al., 2023). Various Industry 4.0 technologies can serve as Poka-Yoke (P-Y) solutions (Lucantoni, et al., 2022). Since Industry 4.0 technologies support the achievement of sustainable development goals, as highlighted in (Mabkhot et al., 2021), it can be concluded that the use of P-Y solutions based on these technologies also has a positive impact on the sustainable development of enterprises. Among others the following technologies can be found in P-Y: augmented reality (Andersen et al., 2009; Chimienti et al., 2010; Azuma et al., 2012), virtual reality (Yin et al., 2017;), Internet of Things (Ramadan and Salah, 2019), wireless technologies (Gladysz and Buczacki, 2018), real time data analysis (Garza and Das, 2001), Big Data Analysis (Muharam and Latif, 2019), mobile technologies (Grout, 2007; Hakkarainen et al., 2008), fuzzy logic (Al-Araidah et al., 2010), and others.

The aim of this paper is to propose a classification table and an evaluation tool supporting the adoption of P-Y techniques that take into account not only product defects, but above all, mistakes resulting in the creation of nonconforming products, as well as mistakes affecting the employee, the production system and the environment. The construction of the tool begins with the classification of possible P-Y techniques to then build a Classification Graph that will support the assessment of the effectiveness of P-Y techniques in relation to specific process conditions encountered in the industrial environment.

The next section of this paper reviews the definition of P-Y. Subsequent to this, the following section describes the methodology used to create a classification for P-Y techniques, along with the proposed Classification Graph. The application is then demonstrated by assessing three distinct P-Y techniques. The final section provides a summary and emphasizes the need for further research in this area.

2. Poka-Yoke definitions

In literature many definitions of P-Y are present. The review of these definitions is shown in **Table 1**. According to some authors, P-Y is a technique which prevents mistakes or, according to others, it is a solution which allows to discover and correct the mistakes that have already occurred.

Other definitions state that these are the solutions which should prevent not the mistakes but their outcomes. Different definitions probably derive from the fact that there are different kinds of P-Y techniques as well as different applications of the same solution.

For example, in the work (Hollnagel, 2004), for the application in IT the author divides P-Y techniques into three types:

- Physical solutions which block the flow of mass, energy or information, and do not depend on the users' interpretation of them (e.g. a wall);
- Functional solutions which might be switched on and off depending on the situation (e.g. a lock or a password), independently from the user's interpretation;
- Symbolic solutions which if require interpretation, appear physically at the moment they are needed (e.g. a safety sign).

Table 1. Poka-Yoke definitions

Definition	References
A mechanism for detecting errors and defects, which inspects 100% of the items, working independently from the operator's attention span	(Shingo, 1988)
A device used to prevent the defect from occurring in a machine or in a process	(Joseph et al., 1996)
A mechanism for detecting, eliminating and correcting errors at their source, before they reach the customer	(Plonka, 1997)
Devices the process is equipped with to prevent the special causes that result in defects, or to inexpensively inspect each item that is produced to determine whether it is acceptable or defective	(Tsou et al., 2008)
The Poka-yoke technique identifies human errors and creates ways to eliminate them, however, it depends on the occurrence of an error in order to prevent its future occurrences. It is any mechanism within a lean manufacturing process that helps an equipment operator to avoid mistakes.	(Lopes et al., 2013)
The systematic practice of eradicating errors by locating their root cause	(Middleton, 2001)
A quality improvement methodology to prevent mistakes from in order to minimize the negative consequences	(Krajewski et al., 2007)
A poka-yoke is the use of a process or design features to prevent errors or the negative impact of errors	(Grout, 2007)
A device that either prevents or detects abnormalities, which might be detrimental either to the product quality or to the employees' safety	(Saurin et al., 2012)
Automatic devices or methods to detect problems before or as they occur using a Poka-Yoke device to minimize the negative consequences	(Al-Araidah et al., 2010)

S. Shingo divided Poka-Yoke techniques according to the goals they have to accomplish in a quality system (Shingo, 1988):

- Source inspection, called proactive Poka-Yoke devices, realized to avoid the occurrence of a defect;
- Self-inspection to detect a defect in the operation in which the defect is generated;
- Successive inspection which detects a defect in the operation that follows the operation in which it was generated;
- Judgment inspection which detects a defect a few operations ahead of the one in which it was generated.

In industry, Zero Quality Control (ZQC) Poka-Yoke takes a variety of forms such as (Evans, 2005):

- 100% inspection;
- Identifying defects as close to the defect source as possible;
- Taking corrective actions concerning a defect in order to avoid the reoccurrence of that defect in the future;
- Designing the processes in order to avoid defects.

In the work (Lazarevic et al., 2019) the authors based on a literature review distinguished the following types of P-Y devices:

- Passive devices P-Y;
- Active preventive P-Y;
- Active, for detection P-Y;
- Hybrid active, preventive;
- Hybrid active, detection.

The presented definitions are useful for classification purposes but focus mostly on product defects which are the consequences of mistakes. While a new approach proposed in this paper focuses on mistakes avoidance. In light of this, a new definition is proposed aimed at supporting the evaluation of P-Y techniques' effectiveness in preventing or detecting various mistakes impacting both, the product and the production process.

In present study, the following definition of P-Y is proposed: *Poka-Yoke is a solution developed to reduce or completely eliminate mistakes that can lead to product nonconformities, machine failures, operator injuries, or environmental threats.*

3. Poka-Yoke classification

Poka-Yoke techniques can be classified according to a number of different criteria. In the work (Saurin et al., 2012) a method for the evaluation of P-Y techniques is proposed. This method is relatively detailed and includes many evaluation criteria. Thus, the question arises if companies are willing to use the method in everyday practice. In the work (Antonelli and Stadnicka, 2016) the Fuzzy Inference methodology is proposed to assess the P-Y solutions. However, especially for SMEs, a less complex method could be recommended.

In this work a straightforward method for the assessment of P-Y techniques is proposed. To allow the application of the method already in the design phase, i.e. before having any quantitative data on the number and type of defects in production, binary evaluation criteria based on the presence or absence of specific characteristics were used.

To propose a classification of P-Y techniques a research in industry was performed. 139 P-Y solutions from 24 companies operating as suppliers in automotive, aviation and metal processing industry were investigated. The analysed P-Y use such technologies as cameras, machine vision, augmented reality, sensors, automation, big data analytics, real-time data processing, barcodes, visualisation, vibrofeeder, and others. The companies were chosen among those that presented their solutions at meetings dedicated to lean manufacturing. P-Y techniques were identified based on industrial expertise and knowledge, and the inclusion criteria were not based on preliminary evaluations.

Figure 1 shows structure of investigated companies and number of studied P-Y techniques. On the base of gathered information a Classification Graph of P-Y solutions is developed (**Figure 2**). The Classification Graph can help with evaluation of effectiveness level of P-Y solutions.

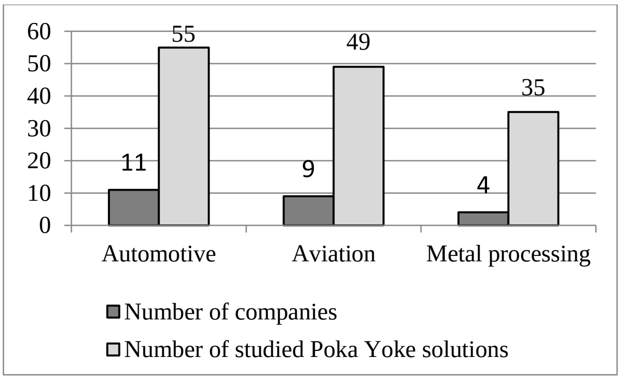


Fig. 1. Investigated companies and Poka-Yoke solutions

During the study of P-Y techniques, the following analyses were conducted:

- Analysis of work performed at a specific workstation, where an operator might make a mistake;
- Analysis of mistakes that were made or could potentially be made;
- Analysis of the consequences of mistakes that occurred or could potentially occur;
- Analysis of existing and proposed P-Y solutions to implement.

Table 2 presents a classification of P-Y solutions summarizing whether the solution prevent mistakes or not. The mistakes may lead to nonconforming products. By implementation of P-Y techniques it is possible to prevent mistakes or to identify mistakes before it leads to production of a nonconforming products. P-Y which are able to discover mistakes very fast will prevent nonconformities but will not prevent time waste and related costs. Therefore, in this study focus is put on preventing mistakes. **Figure 2** presents a graph for the prioritizing of P-Y techniques. In general, there are P-Y techniques that can be very highly effective and others that can have very low effectiveness.

Certainly, it should be clearly underlined that, even if quality control is performed on the entire production, it is impossible to assure the absence of defects. It stems from the fact that none of the systems is absolutely reliable. Failures, fluctuation in power supply, hidden material defects can always emerge in technical devices which are designed to control and monitor a process.

Table 2. Classification of Poka-Yoke techniques

Type of Poka-Yoke	Function	Task	Goal	Effectiveness in mistake proofing
Technical devices	Preventive	Preventing mistakes	Zero mistakes	High
	Corrective	Stopping the process in case of a mistake	Preventing the flow of nonconforming products to the next step of the process	No mistake proofing
	Informative and preventive	Transferring the information concerning the probability of making a mistake	Preventing mistakes	Medium
	Warning	Transferring the information on a mistake made	Disclosing a place for improvement	No mistake proofing
Organization al solutions	Informative	Transferring the information on the proper way to perform a process in order to avoid mistakes	Preventing mistakes	Low
	Corrective	Transferring the information on what to do in case of making a mistake	Preventing reoccurrence of mistakes	No mistake proofing

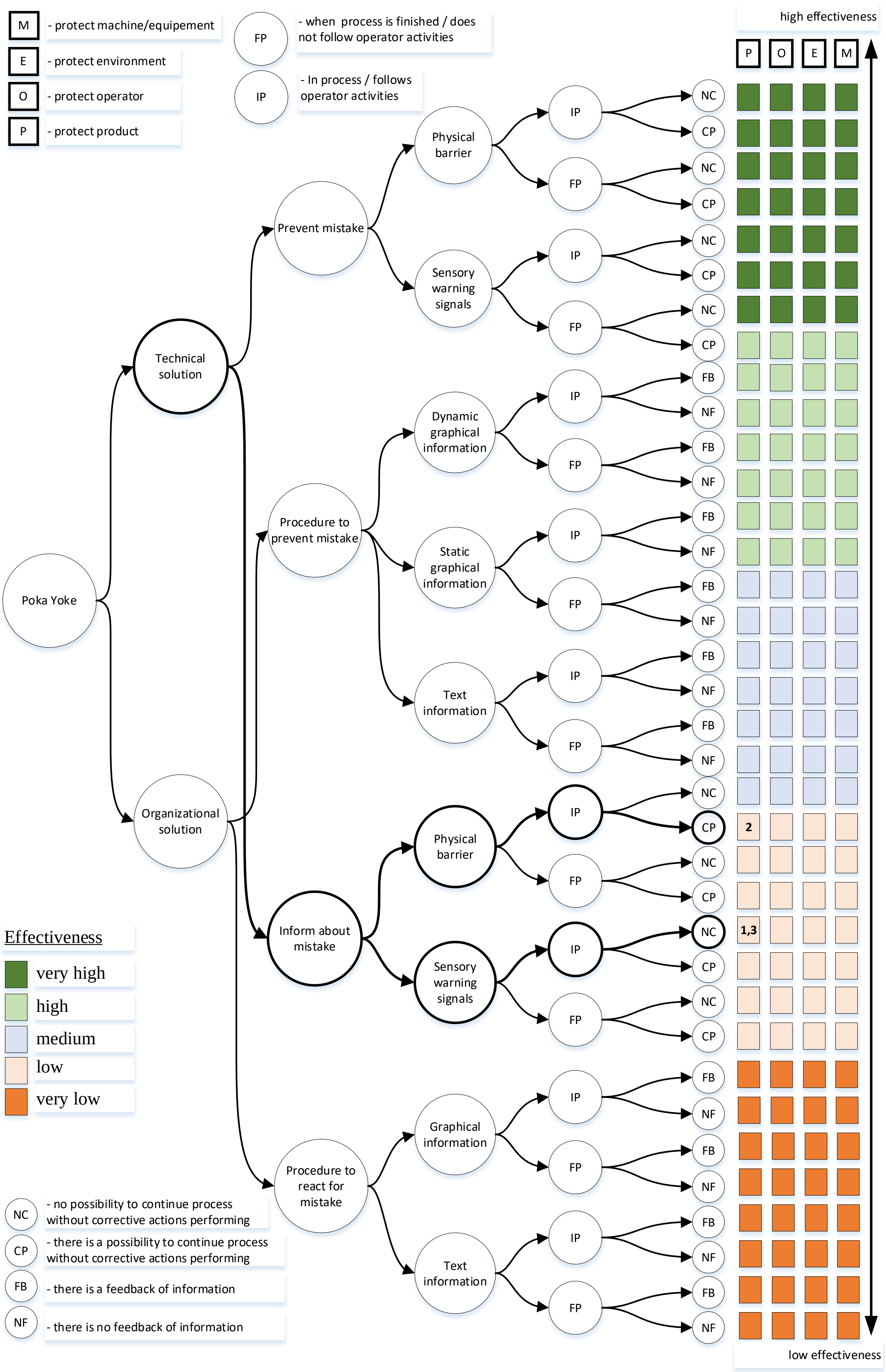


Fig. 2. Classification graph of Poka-Yoke techniques

Lacking a control group, i.e. a set of pieces that are produced without using P-Y, it is not always possible to give a quantitative evaluation of P-Y effectiveness in terms of number of defects avoided.

To place a given P-Y technique on the graph in Fig. 2 it is necessary to make a series of binary or choices: the solution is technical or organisational; is preventive or corrective, it operates through a barrier or through signals; information is given through graphic or textual outputs; P-Y operates during the process or at the end.

We assume that technical devices will have higher efficiency, particularly if a physical barrier is put in place. This barrier will physically prevent mistakes in a process as well as it will stop a process from continuing unless the corrective actions are implemented. In some of the solutions it is possible for an operator to decide if a process is to be continued howsoever without corrective actions. However, such a solution has already lower effectiveness because it depends on a subjective employee's decision (Stewart et al., 2001).

Despite that fact, this solution is attributed with a high level of efficiency assuming that the employees are well prepared for their work. Physical solutions, which warn an operator about the possibility of making a mistake by a sound, vibration or light signal (sensory warning signals), are less effective. However, they also require an adequate operator's reaction before the mistake appears in a process, or before the failure appears in a product.

Further, there are also less effective P-Y techniques which only inform about mistakes that have been made. However, they still allow for a quick reaction and, thanks to that, they reduce nonconformities costs, which can appear in relation to the mistake or which have already appeared. Theoretically, these solutions shouldn't allow, in spite of the mistakes already made, the negative consequences of them. Another group of P-Y technique includes organizational solutions, which exist in the form of procedures prepared for certain processes. Depending on the form of the procedure and the way of information transmission to an operator during the process, the solutions can have different effectiveness. In the proposed classification model, a dynamic and a static way of transmitting the graphical information are taken into consideration. The information can also take the form of a text. The procedures can concern activities which should be done to prevent mistakes or activities which should be done in case a mistake has already been made. It is worth to emphasize that when the information is transmitted successively and follows the process, the solution is more effective. Finally, it is also essential whether the information takes into consideration the actual state of a process, or whether it is independent from what has really been done in the process.

P-Y techniques, which should prevent mistakes in a process or reduce the consequences of mistakes made, should simultaneously protect a product against defects. The proposed method recommends to assess additionally if the P-Y techniques protects a product, an operator, a machine and/or the natural environment against the consequences of mistakes made in the process by an operator.

In the following sections some examples of P-Y techniques are presented, classified and evaluated. The results of this can be seen on the Classification Graph (**Figure 2**) where the numbers (1, 2, 3) representing the analysed case studies have been placed.

For evaluating effectiveness, a 5-level Likert scale was adopted associated to corresponding effectiveness classes: very low for no error prevention, low for information, medium for error identification, high for error identification before it results in a non-compliant product, and very high for error prevention.

4. Case study 1: Kitting process

4.1. Process description

Kitting process of assembly sets is realized manually by operators (Wyskiel, 2014). Elements for kitting are taken from containers and placed into a box. A label, which specifies the contents of the box, is then affixed to it. Each set consists of several elements, making it easy for the operator to make a mistake during the kitting process.

4.2. Poka-Yoke technique description

The work procedure for the workstation equipped with a P-Y solution is as follows:

The computer screen displays a production order containing information about what should be packed in the assembly set. The worker picks the first item from the list and scans its barcode using a barcode reader. The scanned item is then placed into a box. The list updates to confirm that the correct item has been selected. If an incorrect item is taken, a notification will appear on the screen. Once all items are packed, the operator can print a label. This label is then affixed to the box.

The solution presented in **Figure 3** is a technical system that alerts the operator of a mistake when an incorrect item is selected for packing. The operator receives a sound signal and sees a notification on the screen. This alert occurs during the packing process, allowing the operator to rectify the mistake immediately. This means the operator can then select the correct item and pack it, ensuring that the box contains all the necessary elements for assembly.

The system prevents the operator from continuing the process until all necessary barcodes for the set have been scanned.

Fig. 3. Workstation for kitting

Only after scanning can a label be printed and the production order closed. This solution safeguards the product against non-conformities but does not prevent operator mistakes.

4.3. Poka-Yoke classification and evaluation

This is a technical solution designed to mitigate mistakes in kitting processes. While it does not prevent mistakes entirely, it informs the operator when a mistake occurs, such as selecting the wrong component. Although the system cannot prevent the addition of incorrect or extra elements into a box, it ensures that all necessary components are included, thereby preventing the escalation of mistake consequences. On the computer screen, graphical information is displayed along with a sound signal when a mistake is detected during the process, not afterward. The process cannot continue until corrective actions are taken; this means the operator must select and scan the correct item, which is then placed in the box. This solution is aimed at preventing the preparation of nonconforming sets. It does not address operator safety, environmental protection, or machine safeguarding.

The analysis clearly indicates that to enhance the solution, an improvement should be implemented during the handling phase to prevent the operator from selecting the wrong component. This would involve installing a device that automatically discards a part into a discharge bucket if the scanner detects an incorrect barcode. There are several methods for implementing this type of device. Although this improvement does not prevent the mistake itself, it mitigates the consequences of the mistake in the final kitting process. According to the proposed methodology, the effectiveness of this solution is considered to be low.

5. Case study 2: System of laser inspection of rolling bearings' seals assembly

5.1. Process description

A laser inspection system for seals in rolling bearings has been implemented on the production line (Czajka et al., 2010). This line conducts the assembly process using automated control equipment, which operates without direct human intervention (see **Figure 4**).

The seals are transferred from a storage bin and correctly positioned on a bearing by being pushed into place using a manipulator.

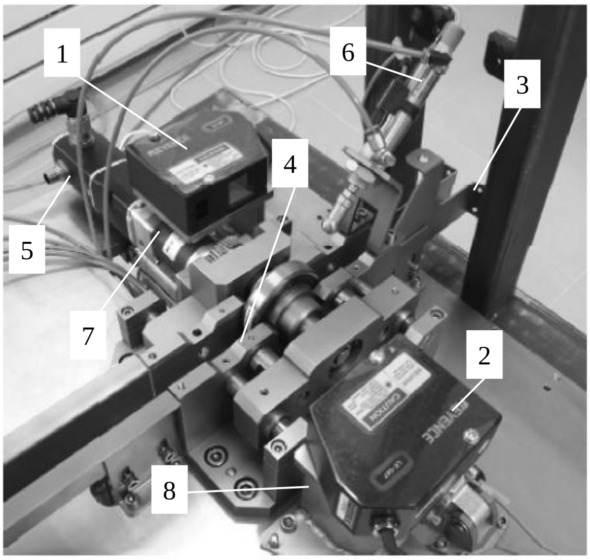


Fig. 4. Control unit: 1, 2 – laser head, 3 – chute, 4 – setting with a bearing in measurement position, 5 – electric drive of bearing rotation, 6 – pneumatic basic elements, 7, 8 – pneumatic drives

5.2. Poka-Yoke technique description

During the process, the following defects in seals can occur (Czajka et al., 2010):

- Absence of a seal in a bearing;
- Seal placed inversely;
- Seal improperly positioned relative to the bearing dimensions;
- Surface of the seal is folded.

These defects are identified by a laser control system. A photo of the control unit is shown in **Figure 4**. Bearings that exhibit any of these defects are segregated from the acceptable ones and classified as nonconforming products.

However, the process continues without immediate corrective actions to address the underlying causes of these defects.

5.3. Poka-Yoke classification and evaluation

The system described is a technical solution that identifies errors in the seal assembly process by using a physical barrier. This barrier prevents nonconforming products from advancing to the next stage of the production process by automatically removing them. Despite this, the assembly process itself is not halted; instead, the control system continues to operate, merely ensuring that flawed products are excluded.

This technical solution does not prevent errors; it merely signals when an error has occurred, specifically identifying seals that are improperly affixed to bearings. The physical barrier ensures that these defective products do not proceed further in the production line. The process continues without interruption, and no immediate corrective actions are taken to address the root cause of the defects. The primary goal of this system is to remove bearings with incorrectly assembled seals from the production line. According to the proposed methodology, this solution is considered to have low effectiveness.

6. Case study 3: Manual Assembly Processes Using Real-Time Image Detection

6.1. Process description

Manual assembly operations in manufacturing are often susceptible to human error, particularly in tasks involving complex sequences or a large number of components. This case study investigates the integration of a pre-trained YOLO (You Only Look Once) image detection model into a factory assembly workflow to provide real-time feedback on part sequencing, aiming to mitigate errors. The YOLO model utilizes computer vision techniques to rapidly analyse a live video feed of the assembly workspace. It compares the current state against a reference database of correct assembly steps. If a part is placed out of sequence, the system generates an immediate visual alert, notifying the worker of the deviation. This report details the YOLO model's architecture, the training process, its integration into the assembly station, and a quantitative assessment of its impact on error rates and assembly efficiency.

6.2. Poka-Yoke technique description

This case study explores a collaborative human--robot assembly strategy, assigning sub-tasks to optimize efficiency and accuracy. The system leverages the strengths of both humans and robots: the robot performs object detection and sequence checks, while the human collaborator handles workpiece manipulation and judges the robot's recognition. This approach facilitates mutual learning – the robot alerts the human operator to placement errors, and the human provides feedback on the robot's object recognition, enabling continuous improvement within the system.

A collaborative assembly operation is performed using an OMRON TM5-900 robot equipped with two distinct camera systems. The robot's integrated 5 Mpx autofocus camera (100mm-∞) facilitates precise positioning. An additional top-mounted camera handles primary object detection tasks (see **Figure 5**).

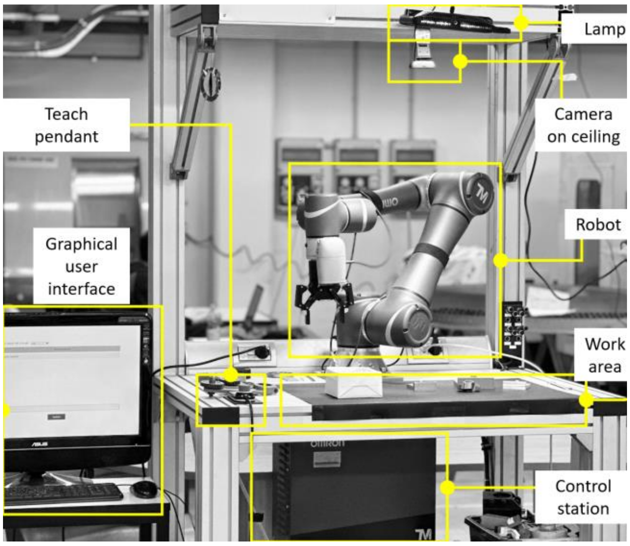


Fig. 5. Workstation

Object recognition is implemented as a pattern recognition problem, utilizing the YOLOv7 deep learning algorithm for classification. YOLOv7's efficient single neural network architecture divides input images into grids, with each cell detecting and classifying objects within its region. Anchor boxes further enhance its accuracy.

YOLO (You Only Look Once) is a highly popular and efficient real-time object detection algorithm. Unlike previous approaches that repurposed image classifiers, YOLO uses a single convolutional neural network (CNN) to perform detection in one pass. This makes it remarkably fast and suitable for real-time applications.

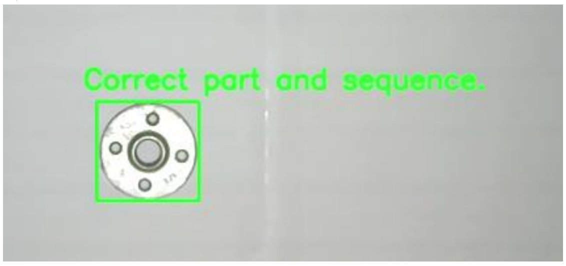
For training, images were resized to 640x640 pixels with a batch size of 16. After 300 epochs, the model achieved an accuracy of 96.7% and a recall of 100%. First, the system establishes the correct assembly sequence: "4 holes, 3 holes, 2 holes, 4 holes square".

The assembly task begins. The worker picks up a part and places it on the designated platform. The camera detects the part type and verifies its position in the sequence.

Possible System Responses are as follow (**Figure 6**):

- Correct Part, Correct Sequence: "Correct part and sequence".
- Correct Part, Wrong Sequence: "Wrong sequence. Please place: (name of next part)".
- Wrong Part: "Wrong part. Please place: (name of correct first part)".

a)



b)

Fig. 6. Two kind of results for part and sequence detection: (a) object is in the list and in the right sequence; (b) object is in the list but in the wrong order

6.3. Classification of the solution

The assembly task begins. The worker picks up a part and places it on the designated platform. The camera detects the part type and verifies its position in the sequence. To summarize:

- The solution is technical – camera is applied to identify the objects;
- Inform about mistakes – when the wrong object is taken by an operator the system informs the operator about the mistake;
- Sonic or light signal – an information will be passed to the operator as voice information;
- In process / follows operator activities – the camera follows operator movements while realizing the process;
- There is no possibility to continue process without corrective actions performing – the software blocks information related to the assembly process step so the operator will not know what to do next before the correct object will be placed in the assembly area;
- The solution protects against the production of a nonconforming product.

From the classification graph it can be seen that this P-Y technique has not so high effectiveness. The solution prevents from production of a nonconforming product but does not prevent from mistakes. It means that operator can make mistake and take wrong component but this will be discovered immediately and the wrong component will not be used in the assembly process. Only time wastes will appear because the operator will have to put down the wrong component and pick up another.

The solution could be more effective if a technical solution or even procedure to prevent mistakes would be implemented in such way that the operator has no possibility to take a wrong part.

7. Discussion

The Classification Graph, as proposed, offers a simplified yet effective approach to evaluating P-Y techniques, particularly beneficial for small and medium-sized enterprises (SMEs) with limited resources. By focusing on objective characteristics and avoiding complex mathematical calculations, the Graph enables a rapid assessment of existing P-Y solutions and provides insights for their improvement. This streamlined evaluation process can lead to substantial cost savings by identifying and rectifying ineffective or inefficient P-Y implementations.

In terms of cost-effectiveness, the Classification Graph aids in prioritizing P-Y techniques based on their potential impact on error reduction and overall process improvement. By identifying high-impact areas for intervention, companies can allocate resources more efficiently, focusing on implementing or enhancing P-Y solutions that offer the greatest return on investment. This targeted approach not only minimizes costs but also maximizes the effectiveness of P-Y implementation, leading to improved quality, reduced waste, and increased productivity.

Furthermore, the Classification Graph indirectly contributes to sustainability efforts. By promoting error prevention and reduction, P-Y techniques inherently support resource conservation and waste minimization. For instance, preventing defects in the assembly process reduces the need for rework, scrap, and additional material consumption. Additionally, P-Y solutions that focus on operator safety and environmental protection directly align with sustainability goals by minimizing the risk of accidents, injuries, and environmental damage.

The case studies presented in this paper illustrate the potential of P-Y techniques to enhance both economic and environmental sustainability. For example, the laser inspection system in Case Study 2, while not directly preventing errors, ensures the removal of non-conforming products, thus preventing further processing and waste of resources. Similarly, the real-time image detection system in Case Study 3, although not fully preventing mistakes, enables immediate error detection and correction, minimizing the production of defective products and associated waste.

8. Conclusions and future research

In conclusion, the Classification Graph serves as a valuable tool for companies seeking to improve their production processes through the effective implementation of P-Y techniques. By facilitating a rapid and objective evaluation of P-Y solutions, the Graph enables companies to identify areas for improvement, prioritize interventions, and optimize resource allocation. This, in turn, leads to cost savings, increased efficiency, and a positive impact on sustainability efforts.

Future research should focus on developing a comprehensive catalogue of P-Y techniques. This catalogue would assist companies in systematically designing effective P-Y solutions. Additionally, evaluations of proposed P-Y techniques should include a thorough analysis of their economic impact before implementation. This economic assessment should cover both the likelihood of mistakes reduction and the direct and indirect costs associated with the implementation of these techniques. Conducting such evaluations is essential to ensure that decisions regarding the adoption of specific P-Y solutions are economically justified and sustainable.

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