

Article

Integrating Industry 4.0 Technologies into 8D Methodologies: A Case Study in the Automotive Industry

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Featured Application

A framework using Industry 4.0 technologies to implement all 8D steps. Here, it is used in automotive manufacturing; however, it can be used in other industries.

Abstract

This paper presents the application of the 8D method to a case study in the automotive industry, combined with the development of a pilot framework that integrates Industry 4.0 technologies—Artificial Intelligence (AI), Internet of Things (IoT), and advanced IT tools. Unlike traditional 8D implementations, the proposed solution introduces several innovations: (i) AI-based complaint analysis with automated keyword detection and classification and localization of batches in the warehouses achieving a 100% accuracy rate in categorizing root causes; (ii) IoT-enabled non-invasive monitoring of production parameters for tests and logs, reducing fault rate to 0 for current case study; (iii) digital cataloging and storage of corrective and preventive actions, improving retrieval speed of past solutions by 300 times (from 300 min to less than 1 min); and (iv) automated reporting tools, cutting the report preparation time from hours to minutes. Through these contributions, the system enhances both responsiveness and prevention, leading to an observed 100% reduction in fault recurrence associated with current case study and an estimated 75% decrease in customer complaints regarding defects occurring throughout the production sector where the pilot was implemented. In addition to the practical improvements, this work extends the literature on digitalized quality management by demonstrating how the 8D methodology can be effectively re-engineered with Industry 4.0 components. Comparative analysis against the enterprise's conventional 8D system and against recent alternative approaches confirms that our framework provides measurable benefits in the speed, accuracy, and sustainability of problem-solving processes.

Keywords: 8D analysis; Artificial Intelligence (AI); large language model (LLM); Internet of Things (IoT); reports engine



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1. Introduction

The global automotive industry is changing rapidly, and major companies must make a series of strategic adjustments to retain their customers and avoid falling behind. They must ensure high-quality products, delivered on time, at a competitive price. The identification and resolution of problems represent an ongoing concern within organizations in this sector, as this approach ensures continuous improvement, while the quality of automotive components is a prerequisite for automated production in a smart company within the context of Industry 4.0 [1,2].

These objectives can only be achieved if companies implement a quality management system in compliance with the requirements of the IATF 16949:2016 standard of the International Automotive Task Force, while also ensuring that their suppliers do the same [3,4]. A quality management system provides customers with confidence that enterprises are capable of consistently delivering products that meet requirements. According to the IATF 16949:2016 in automotive supplying companies, based on this standard, organizations shall have a defined process for problem-solving leading to root cause identification and elimination. All levels of the organization are included in the problem-solving process [4]. Adopted and improved by the Ford Motor Company (Detroit, MI, USA), Eight Disciplines, G8D or 8D, founded by the US government following World War II as MIL-STD 1520, is a disciplined process that addresses problem solving via a methodical and analytical method, addressing root causes to eliminate the source(s) of the concern, as required by the IATF 16949:2016 [3]. The 8D method is widely adopted in the automotive industry and other manufacturing sectors and industries worldwide [4].

The 8D method serves as an interface between supplier and customer. It is used by the supplier as a response to the complaint filed by its customer. It applies to all product nonconformities under the supplier's responsibility, and the primary objective is to implement and consolidate corrective actions within the quality management system. The output of the 8D method is an 8D report, which consists of eight steps following the Plan-Do-Check-Act (PDCA) cycle.

The new benefit identified in this case study for quality control, not mentioned in previous studies or in studies like [5,6], is the combination of many tools of quality management, especially Pareto analysis, RE analysis, and the five whys technique with the most modern technologies: AI, IoT, and dedicated reporting engines. As a result, a synergistic process is developed. The quality of the process has been improved because the root causes of the problems have been identified and removed.

The response time of our solution is significantly lower compared to the methods in place before its implementation in an experimental model and then as a pilot. The main innovative element is the design of a complete framework for the 8D analysis of a complaint.

This paper proposes and validates a complete framework for 8D analysis, applied to a real case from the automotive industry, in which positioning deviations of holes on a structural component used in the support assembly of refrigeration units for trailers were identified and corrected. The main contribution consists of the development of a hardware–software solution that integrates Industry 4.0 technologies—Artificial Intelligence (AI), Internet of Things (IoT), and reporting engines—across all stages of the 8D methodology. Unlike previous approaches, the proposed solution enables automatic complaint analysis, rapid identification of affected batches, root cause detection through digital simulation, and automated generation of documentation (FMEA, action plans, lessons learned).

This solution was implemented in a pilot model, and the results confirm its effectiveness: response time was reduced from hours to under one minute, nonconformities were eliminated, and non-quality costs were significantly reduced. The 8D audit validated the

effectiveness of the corrective actions, and the process was stabilized and optimized. Thus, this paper provides a practical, scalable, and replicable contribution to the digitalization of complaint resolution processes in the automotive industry.

The Literature Review (Section 2) presents studies conducted in the fields addressed in this paper and explains how our proposed solution brings improvements. In Materials and Methods (Section 3), the 8D methods are detailed based on the case study presented in this article. The Case Study (Section 4) describes the actual case study, along with the technologies involved in implementing the 8D analysis. Finally, the paper concludes by presenting our Results (Section 5) and Conclusions (Section 6).

2. Literature Review

Along with other methods, the 8D method improves production quality and reduces customer response time and overall reduces failure rates [7]. The 8D methodology involves cross-functional teams working together to solve quality problems, using a structured eight steps, following the Plan-Do-Check-Act cycle (PDCA), shown in Table 1 [8].

Table 1. Steps for the 8D methodology.

PDCA	Steps	Description
Plan	D1. Issue details	The working team must define the problem very clearly and precisely. The root cause of the problem is found by using quality tools like the 5W & 2H (What, Where When, Why, Who & How, How Many) Affinity Diagram [9].
	D2. Immediate checking actions	This stage aims to initiate immediate verification actions to assess whether the reported defect is also present in other similar products or within the same family of parts. The existing stock of similar products is analyzed to detect other products with the same nonconformity risk.
	D3. Initial analysis	This step is used to identify the causes of the failure to detect the problem: In what place should the nonconformity be detected? Why wasn't the nonconformity detected?
	D4. Immediate action plans	In this stage, immediate action plans are defined and implemented to protect internal and external customers from the problem until permanent corrective actions can be put in place.
Do	D5. Final analysis	The aim of this step is to obtain a real and complete of the situation to identify the root causes and to decide the optimum actions required for the treatment of the causes.
	D6. Final action plan	The purpose of this step is to develop an action plan to eliminate the root causes identified in steps 3 and 5. Permanent actions are analyzed and implemented to prevent the recurrence of the problem.
Check	D7. Action plan confirmation.	Step 7 of the 8D methodology is very important because it allows for the closing of the action plans. The effectiveness of the final action plans is verified. This is a key step aimed at preventing the recurrence of the quality problem.
Act	D8. Prevention problem recurrence	This step involves modifying specifications, updating training, reviewing workflows and improving practices and procedures. These changes are necessary to prevent recurrence and similar problems in the future.

The literature review mentions several successful case studies wherein the 8Ds method was applied. For instance, this study applied the Ford 8D method to a semiconductor original equipment manufacturer (OEM) in Taiwan, focusing on avoiding yield declines caused by tester time domain reflection (TDR) in wafer testing [8]. Kumar, S., Verma, M., and Dubey, D. (2023) [10] highlight the importance of customer satisfaction in industry and analyze the utility of the Eight Disciplines (8D) method as a tool for problem-solving and quality improvement. The authors emphasize its role in root cause analysis and in applying the PDCA cycle, both for external complaints and internal nonconformities. A case study

conducted in an ISO-certified manufacturing company demonstrates the effectiveness of the method in reducing defects and improving quality [10].

Kempel, M., Richter, R., Deuse, J., Schmid, S., and Schulte, L. (2023) [11] carry out an analysis addressing the profound changes in the automotive industry caused by the electrification of the powertrain. In this context, the authors propose an innovative IT application based on knowledge graphs to support problem-solving using the 8D method. The technical implementation relies on OWL ontologies and SKOS taxonomies compliant with W3C standards. The solution was evaluated at a Tier-1 supplier in the field of electrified mobility, demonstrating that digitalization can significantly reduce the time and effort required to describe and solve problems [11].

Uslu Divanoğlu and Taş (2022) consider the 8D method as a quality management tool for eliminating chronic problems in the automotive industry [12]. They integrate 8D with other technologies such as Value Stream Mapping (VSM) and Failure Mode and Effects Analysis (FMEA), proposing a new model within the lean production framework. Results show a dramatic reduction in PPM (Parts per Million) levels (from 1071 to nearly 0), confirming the positive impact of 8D on process performance and quality cost reduction.

Rakesh Kumar Phanden, Aaryan Sheokand, Kapil Kumar Goyal, Pardeep Gahlot, and Halil Ibrahim Demir (2022) [6] carry out a deeper analysis of the 8D methodology with respect to the automotive manufacturing sector, focusing on the sequential steps of problem-solving and the associated tools. The authors discuss both advantages and challenges (wrong team selection, lack of data, time limitations), emphasizing that 8D is not a one-time intervention but a continuous management choice to respond to customer complaints. The paper compares 8D with the DMAIC methodology, underlining their complementarity as PDCA-based and data-driven approaches, respectively [6].

Huszák, C., Pinke, P., and Kovács, T.A. (2025) review classical root cause analysis methods, such as 5W, Fishbone Diagram, Fault Tree Analysis, and Event Tree Analysis, and show how these can be complemented by PDCA, FMEA, and the 8D method. The authors underline the integrative role of these tools in preventing potential failures, especially in safety-critical components [13].

In contrast to the previous works, Ichimov M.A.M., Popescu M.V., Negoita O.D., Costea-Marcu I.C., and Moiceanu G. (2025) focus more on the integration of computer sciences into organizational processes and on digital data security. While it does not directly address the 8D method, the study is relevant in the context of applying IT systems and digital solutions to support efficiency, process optimization, and quality management [14]. From the analysis of existing works (studies, papers, projects including commercial solutions), there is no comprehensive approach to the 8D analysis that integrates AI, IoT, and digital technologies for automatic report generation as in our solution. However, there are works that address different branches of the 8D analysis and use technologies like those we present.

In the field of using NLP/AI for complaint analysis, Yao, L., Huang, H., & Chen, S. H. (2020) propose the automatic extraction of relevant terms from customer complaint texts to facilitate problem analysis in production [15]. The technology used here consists of classical text mining algorithms (TF-IDF, clustering). The study does not use LLMs or advanced AI. Bozyiğit, F., Doğan, O., and Kılınç, D. (2022) [16] use neural networks for the automatic classification of complaints into defect categories. The advantages are accuracy greater than 90% and fast integration into ERP systems. As a limitation, their approach does not include email integration or a complete 8D pipeline. Our solution uses LLMs (large language models) for automatic keyword identification from email. It directly integrates the 8D pipeline, which is an advantage over many existing solutions [16].

In the area of computer vision for stock identification, Xie, T., & Yao, X. (2023) presents the use of cameras for locating pallets and products in the warehouse [17]. The technology used is YOLOv5 for object detection in images. However, the paper does not integrate directly with quality management or 8D solutions. Our solution ensures a direct connection between image analysis and the 8D steps.

In IoT for data acquisition, Rahmatov, N., Paul, A., Saeed, F., Hong, W. H., Seo, H., & Kim, J. (2020) present the integration of sensors and video cameras for real-time monitoring of production lines. They use edge computing to reduce analysis time [18]. Here too, the integration into the 8D workflow is not detailed. Oliveira, D., Alvelos, H., & Rosa, M. J. (2025) identifies the trend of integrating IoT and AI for predictive maintenance and quality management [19]. Many works describe the integration into 8D only theoretically. Our solution performs non-invasive data acquisition directly from processes and on-server analysis, all more integrated than in many current solutions.

In terms of report generation automation, Sima, D., Potra, S., & Pugna, A. (2024) present the digitization of documentation for 8D [20]. The technologies used here are form templates, autofill, and RPA. The study does not use AI or LLM for report generation. Our solution has a report engine module with a dynamic template that allows for automatic data extraction, with a significant advantage in generation time (a few seconds).

In the area of AI for root cause analysis, Pietsch, D., Matthes, M., Wieland, U., Ihlenfeldt, S., & Munkelt, T. (2024) use machine learning for analyzing defect causes [21]. The method reduces analysis time and finds hidden patterns. Here too, the integration into the full 8D process is not detailed. Our solution integrates AI and possible scenarios directly into the 8D workflow.

There are also works that present 8D analysis in case studies, as in our work:

In the paper Mario Hermann, Isabel Bucker, Boris Otto (2020), the stages of applying Industry 4.0 concepts in several quality management systems are presented [22]. Their application was performed on a hypothetical case study presented by the industry. Our article presents a complete framework for 8D analysis focused on a real case study with impact on quality improvement.

A complete treatment of 8D analysis in a case study was also presented in the Realyvásquez-Vargas, A. Arredondo-Soto, K.C. García-Alcaraz, J.L. Macías, E.J (2020) [23]. As in our study, the paper goes through all the steps of 8D analysis for custom cable assembly. In addition, our paper presents the involvement of modern technologies specific to Industry 4.0 in improving information acquisition, identification and generation of reports specific to 8D analysis. Also, a presentation of a case study with a complete treatment of 8D analysis in the tobacco industry was carried out by Rajeev R, Maddireddy C G R, Annam L N, Utlapalli L N, Md Saeedur R (2022). Here, the results of the analysis application and the impact on indicators such as PPM and the cost of non-compliance were presented [24]. The solution we proposed brings improvements in the analysis by introducing technologies that also affect the analysis time and reduce the future number of complaints that may arise from customers. An interesting work is also Mahmood, Khalid (2023), which presents an 8D analysis for leakage current proof circuit [1]. The analysis, along with the specific reports and indicators, resulted in a work procedure that improves the quality of the products involved in production (the use of a water-based solvent). In our solution, all the results of the 8D analysis are stored and then reused for other cases; thus, a technological solution resulting from the one in the above-mentioned works would be associated with other possible failures for predictive maintenance.

The main innovative element introduced in this article is the existence of a complete 8D analysis implemented using IT, AI, IoT, and cloud technologies—essentially, Industry 4.0 technologies. As mentioned, partial implementations can be found in other works as

well. What we have contributed in this paper is a unified solution that combines all 8D components into a hardware/software framework. This pilot study can certainly be further developed into a commercial solution.

3. Materials and Methods

3.1. Analysis of the Component

The subject of the analysis is a component made from a rectangular steel tube with dimensions of 60 mm × 40 mm × 4 mm, fabricated from structural steel grade S235JRH (Figure 1). This material is characterized by mechanical and chemical properties defined according to applicable standards, and its chemical composition is presented in Table 2.

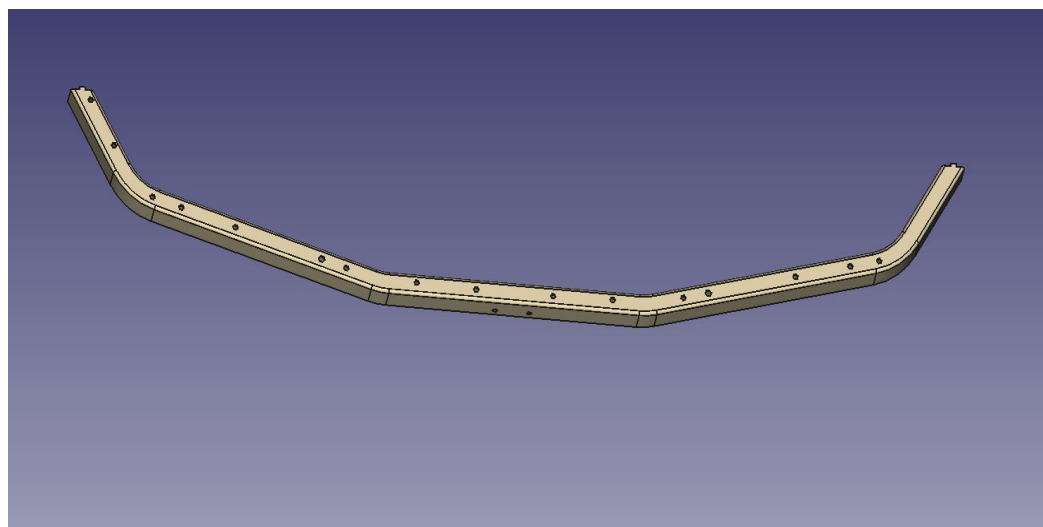


Figure 1. Manufacturing drawing of the component.

Table 2. Chemical composition of material according to EN10219-1.

Material: S235JRH										
C [%]	Si [%]	Mn [%]	P [%]	S [%]	Al [%]	Ni [%]	Mo [%]	Cu [%]	V [%]	Ti [%]
0.064	0.017	0.34	0.012	0.01	0.039	0.02	0.002	0.02	0.003	0.001

Element 11, as indicated in Figure 2 of the technical drawing, represents a critical structural part of the welded assembly used as support for refrigeration units mounted on truck trailers. The component is manufactured through a sequence of operations including laser cutting, bending, and 3D laser cutting, which ensures precise execution of the mounting holes. After processing, the element is integrated into the assembly by welding, contributing significantly to the structural reinforcement and to the even distribution of the loads generated by the refrigeration unit.

Due to its strategic positioning, element 11 stabilizes the entire frame, preventing deformations caused by vibrations and mechanical stresses during operation. It ensures the preservation of the assembly's geometry and provides a reliable base for securing the refrigeration equipment, thereby guaranteeing the safe and durable performance of the support structure. The component is made of structural steel, treated for corrosion resistance, and has a total weight of 10.762 kg, which significantly enhances the overall strength and reliability of the assembly.

The analyzed component is used within the assembly of the refrigeration unit support for truck trailers (Figure 2).

The component is made from a rectangular tube, cut using the Prima Power Laser Next cutting equipment (manufactured by Prima Power, Italy, headquartered in Collegno-Tuino), as shown in Figure 3. The Prima Power Laser Next is a laser cutting system used in the industrial sector, designed for the mass production of steel automotive components. It is currently considered the fastest 3D laser cutting equipment in the world.

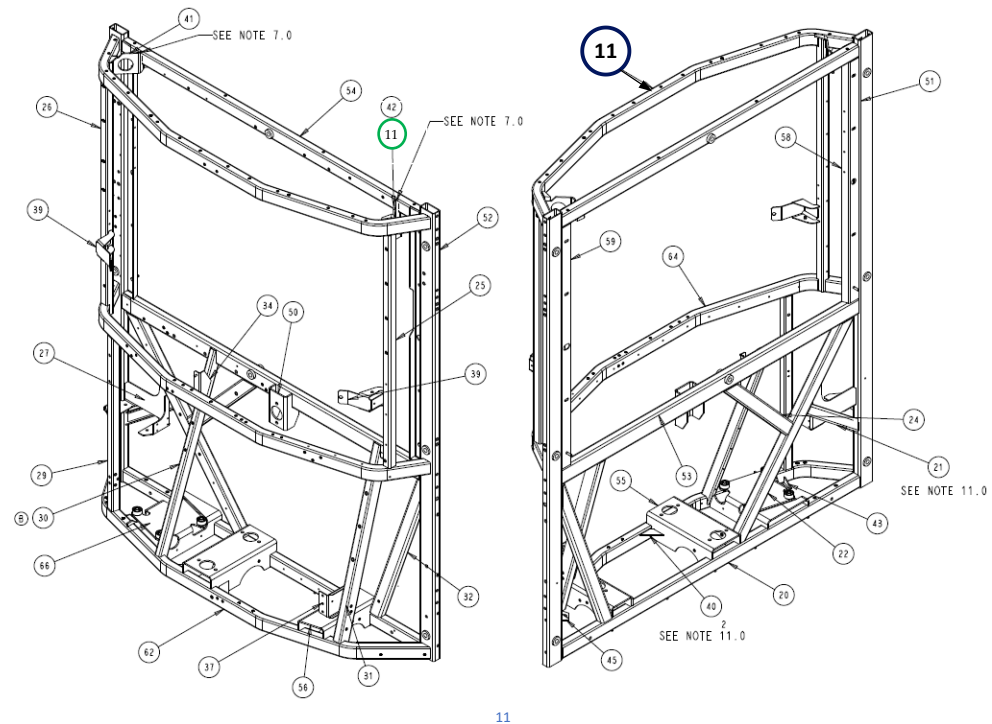


Figure 2. Refrigeration unit assembly.

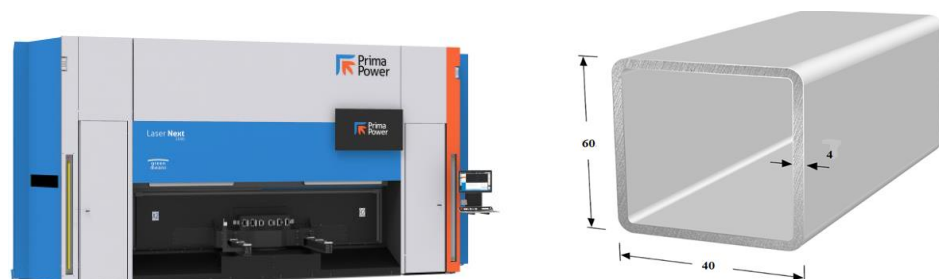


Figure 3. Prima Power Next laser cutting equipment.

By using IoT, real-time monitoring of equipment parameters is achieved, along with the ability to modify (configure) the cutting equipment according to requirements. This allows for the identification of issues that arise during operation, with corrections made based on problems detected through quality analysis. Communication with the equipment enables parameterization and analysis of the impact of such adjustments.

3.2. Structure of the Case Study

The case study presented in this report is structured in a clear and methodical manner, following each essential stage of the process for identifying and resolving a problem reported by the client (Figure 4). Within this process, each element of the problem is systematically analyzed, starting with the client's initial complaint and continuing with the investigation of possible causes.

This approach allows for a deep understanding of the problems encountered and ensures the identification of effective solutions. The client's complaint, which represents

the starting point of the analysis, provides essential data to assess the impact and scope of the problem. After establishing the context, relevant indicators are analyzed, and specific techniques are applied to diagnose the root cause, thereby preparing the basis for implementing effective solutions.

To systematically address and resolve these issues, the 8D method (Eight Disciplines Problem Solving) was used, a standardized tool recognized for its effectiveness in managing and solving complex problems across various industrial sectors. This method is based on a series of essential steps that help identify root causes and implement effective corrective actions.

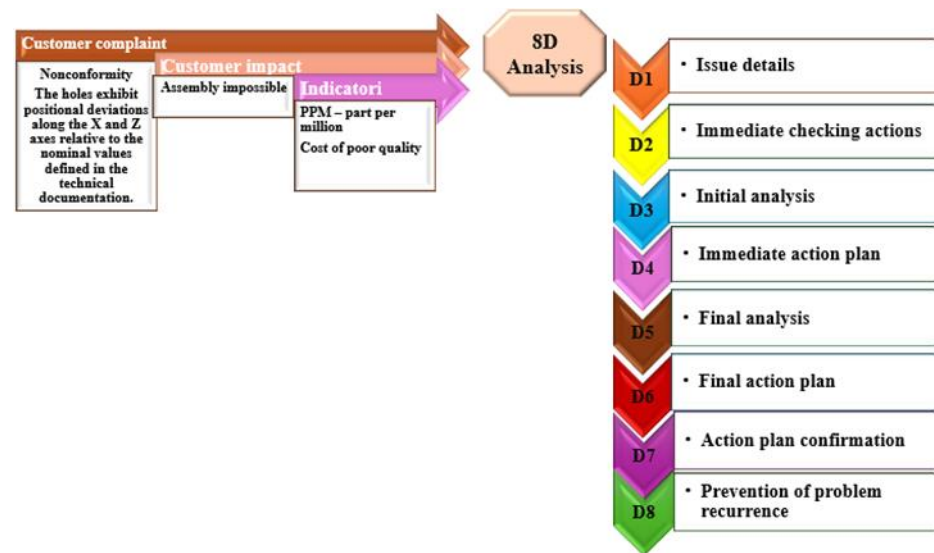


Figure 4. Structure of the case study.

The 8D method includes a series of precise stages for problem analysis and resolution, ensuring both the immediate mitigation of effects and the prevention of recurrence.

Ultimately, the application of the 8D methodology focuses on ensuring a definitive and lasting solution, which not only resolves the current problem but also contributes to the continuous improvement of the involved processes. The resolution process does not end with merely confirming the effectiveness of the solutions; it also includes preventive measures to avoid the recurrence of the same issue. By implementing an action plan that addresses both the immediate and root causes of the problem, a long-term impact on process quality and reliability is achieved.

Thus, the 8D methodology not only helps solve current problems but also strengthens and optimizes organizational processes to prevent similar difficulties from arising in the future.

In the next session the case study itself is presented followed by a presentation of the solution used to implement the 8D analysis.

4. The Case Study

4.1. Presentation of Customer Complaint

Compliance with technical specifications is essential to ensure the conformity of finished products. However, following an inspection carried out by the customer, positioning deviations of the holes in relation to the X and Z axes were observed, compared to the nominal values specified in the technical documentation. This nonconformity was reported through an official complaint, highlighting its negative impact on the accuracy of the final assembly and the assembly process. Figure 5 illustrates the flow of the customer complaint management process. The arrows indicate the logical sequence and causal relationships

between the stages of the process—from the receipt of the complaint, its analysis, and the production stoppage to the final consequences on non-quality costs. The direction of the arrows highlights the flow of information and the evolution of the complaint's impact on organizational performance.



Figure 5. Receipt of customer complaint. The arrows indicate the logical sequence and causal relationships between the stages of the process.

According to the data provided, the deviations exceed the allowed tolerances, which may affect the product's functionality and cause difficulties during assembly. The complaint was submitted on 20 March 2025, and internal investigations confirmed that the dimensional deviations exceed the acceptable limits according to client requirements. According to the complaint, the nonconforming batch contains 300 defective pieces, representing the entire quantity of delivered parts.

This analysis aims to identify, using the 8D method, the causes that led to these deviations and to propose corrective actions to prevent similar situations in the future.

4.2. Impact Analysis on Quality Indicators

The nonconformity had a direct impact on the performance indicators of the production process. External client PPM (Parts per Million) increased, reflecting the number of defective parts detected after delivery, while internal PPM also increased, indicating a higher defect rate identified during internal inspection. In addition, non-quality costs rose significantly, both due to scrap and rework required, as well as potential costs generated by corrective actions and possible returns.

To analyze and control deficiencies in the production process, the following performance indicators are monitored:

- PPM—Parts per Million—External Client; maximum allowable value: 50,000 (5%);
- PPM—Parts per Million—Internal Nonconformities; maximum allowable value: 20,000 (2%);
- Non-quality costs.

PPM—Parts per Million—External Customer

This indicator is evaluated monthly by analyzing data represented graphically, including the evolution of external PPM, the established target value, and the volume of parts produced during the respective period.

According to the data presented in Figure 6, the maximum allowable threshold of 40,000 PPM was exceeded, indicating an increase in the number of nonconforming products delivered to the client.

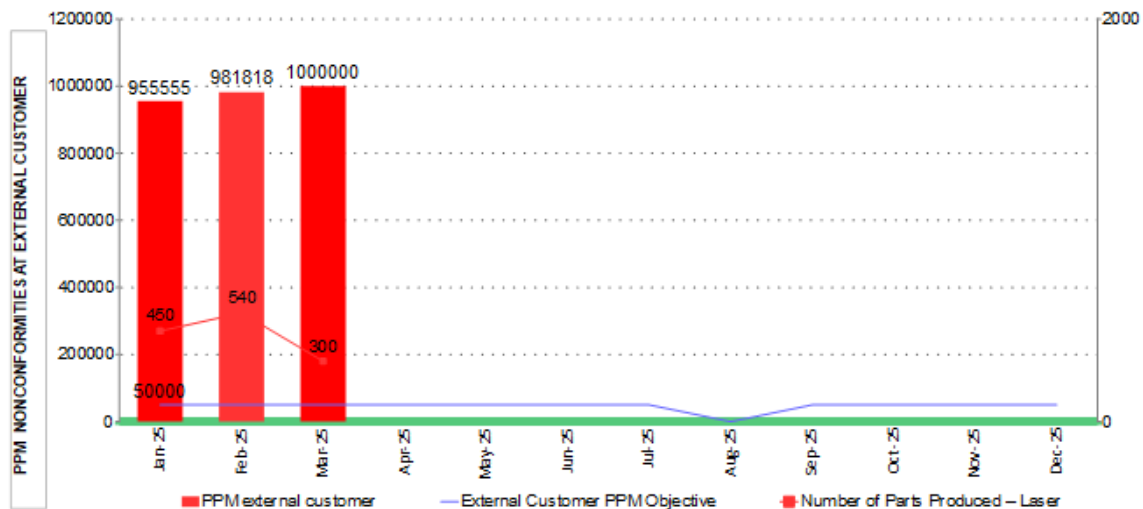


Figure 6. External customer PPM Chart.

The established objective is to maintain this indicator below the imposed limit, as any exceedance leads to increased quality-related costs, including expenses for repairs, returns, and necessary corrective actions.

PPM is calculated using the following formula:

$$\text{PPM} = \frac{\text{Nonconforming parts}}{\text{Delivered parts}} \times 1,000,000 \quad (1)$$

Produced/Nonconforming Parts:

- January: 450 parts delivered/430 nonconforming parts;
- February: 550 parts delivered/540 nonconforming parts;
- March: 300 parts delivered/300 nonconforming parts.

PPM—Parts per Million—Internal Nonconformities

Like the external customer PPM indicator, this parameter is monitored monthly through graphical analysis of its evolution, including the established target value and the total number of parts produced. It provides an overview of the level of nonconformities identified in the internal manufacturing process.

According to the data illustrated in Figure 7, the PPM value for internal nonconformities exceeded the maximum allowable threshold of 20,000, indicating an increase in defects detected before delivery. To maintain quality standards and optimize production processes, the established objective requires keeping this indicator below or at the imposed limit. Exceeding this threshold may indicate deficiencies in process control and the need for appropriate corrective measures.

Produced/Nonconforming Parts

- January: 450 parts produced/20 nonconforming parts;
- February: 550 parts produced/10 nonconforming parts;
- March: 320 parts produced/20 nonconforming parts.

Non-Quality Costs

According to the data presented in Figure 8, the non-quality cost value exceeded the maximum allowable threshold of 500 euros, indicating an increase in losses generated by nonconformities. Keeping this indicator below the established target level is essential for

optimizing operational efficiency and reducing the financial impact of defects. Exceeding this threshold signals the need for a detailed analysis of the causes and the implementation of preventive measures to improve processes.

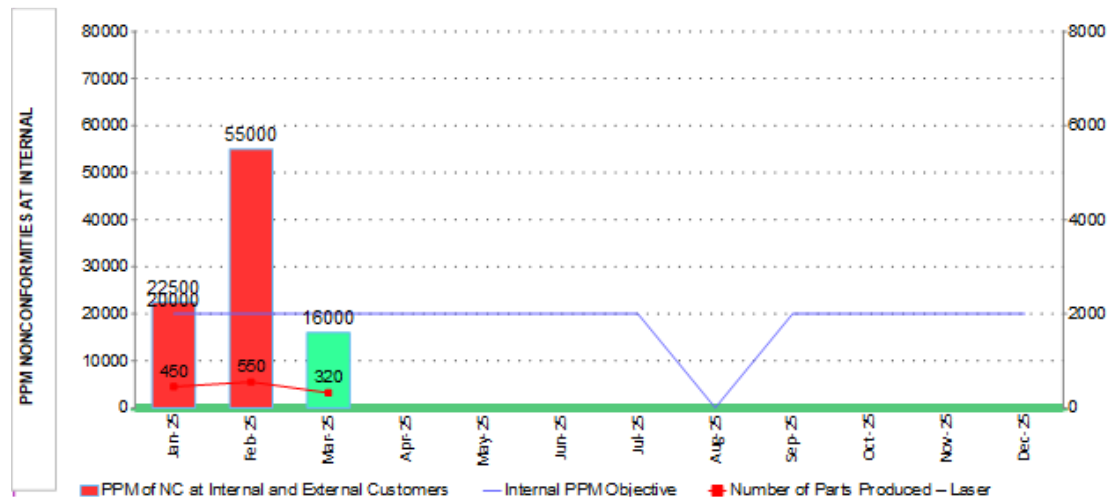


Figure 7. Internal customer PPM chart.

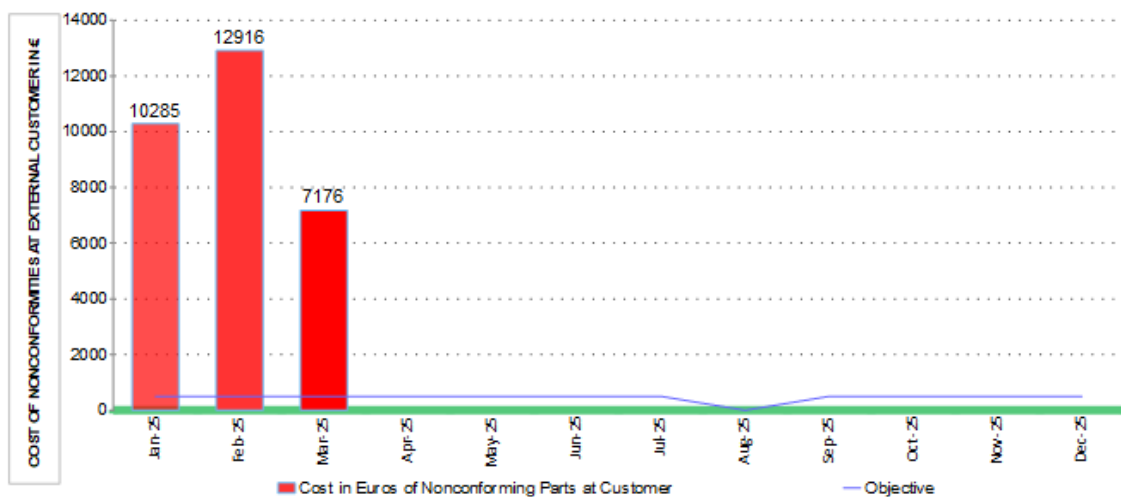


Figure 8. Non-Quality cost chart.

Non-quality costs are calculated using the following formula:

$$C_{NC} = C_R + C_S + C_E + C_P \quad (2)$$

where

- C_{NC} = Total non-quality cost;
- C_R = Scrap cost (eliminated nonconforming parts);
- C_S = Cost of repairs and rework;
- C_E = Cost of additional inspections;
- C_P = Cost of penalties, complaints, and returns.

The nonconformity had a direct impact on the performance indicators of the production process. External customer PPM (Parts per Million) increased, reflecting the number of nonconforming parts detected after delivery, while internal PPM also recorded an increase, indicating a higher defect rate identified during internal inspection. In addition, non-quality costs rose significantly, both due to the required scrap and rework, as well as potential costs generated by corrective actions and possible returns—see Table 3.

Table 3. Costs for case study.

Costs		
January	February	March
$C_{NC} = 10,285$ Euro	$C_{NC} = 12,916$ Euro	$C_{NC} = 7176$ Euro
$C_R = 10,285$ Euro	$C_R = 12,916$ Euro	$C_R = 7176$ Euro
$C_S = 0$	$C_S = 0$	$C_S = 0$
$C_E = 0$	$C_E = 0$	$C_E = 0$
$C_P = 0$	$C_P = 0$	$C_P = 0$

Our proposed solution uses IoT and big data analysis to determine equipment parameters. It involves real-time data acquisition from equipment and their analysis to assess the impact of a complaint. Starting from the complaint (current case), a series of hypothetical cases (variations) can also be generated, and AI can be used to analyze the equipment involved and identify those that can be reconfigured to reduce the probability of failure. The outputs for determining the impact of the analysis are quality indicators (external and internal PPM) as well as the costs of non-quality.

The estimation of the impact of nonconformity can be carried out through

- The existence of a digital twin model of the production process.
- Real-time communication with all equipment involved in the production process.

This is achieved through the use of IoT interfaces. The IoT interface enables both automatic configuration and continuous real-time monitoring of the equipment. In this way, a complete capture can be made of all operations performed by the equipment (and indirectly by the operator who handled the equipment).

The development of the process model was carried out by introducing the equipment parameters (input configurations, possible commands, outputs) as well as capturing the process, also using IoT interfaces. This makes it possible to generate a digital twin that can even replicate potential inaccuracies. From this point, we have two directions:

AI-based analysis of potential problems that may arise, by simulating at the digital twin level and determining the correspondence with the actual flow captured Via IoT. This way, during the production process, potential issues can be predicted and detected before they occur.

Actual analysis of a problem reported by a customer and rapid determination of its causes by simulating its impact at the digital twin level on production. In this case, the solution complements the “classic” preliminary and final analysis methods from 8D, improving the analysis process and reducing the client’s response time.

D1—Issue details

On 20 March 2025, a complaint was received reporting deviations in the positioning of holes relative to the X and Z axes, compared to the nominal values specified in the technical documentation. According to the report, the issue was identified in a batch of 300 parts, all considered nonconforming due to these deviations.

The reception was carried out Via email. A software module automatically retrieved the email, analyzed it, and performed a classification using intelligent email analysis to determine the type of complaint.

To clarify the situation, an analysis of the affected parts, returned by the client, was conducted using the information presented in Table 4. This analysis revealed that the holes were produced with either constant or variable deviations from the specified coordinates, suggesting a possible repetitive issue in the machining process or a set up error.

The problem details indicate a direct impact on the final product quality, as incorrect hole positioning may affect assembly or overall functionality. The nonconformity was characterized as dimensional in nature, with significant deviations from the allowed tolerances, justifying the classification of the parts as nonconforming.

This step aims to describe the problem as accurately as possible to support subsequent investigations into the root cause and to properly justify the corrective actions to be taken.

Table 4. Issue details.

D1. Issue Details		Date Alert: 20 March 2025	
Report Nr:	1		
Customer:	X	Affected Quantity	300 parts
Problem Description:	Positioning deviations of the holes in relation to the X and Z axes compared to the nominal values specified in the technical documentation		
	Repetitive problem:	YES	NO

D2—Immediate checking action

As a result of the received complaint, immediate verification actions were initiated to assess whether the reported defect is also present in other similar products or within the same family of parts.

The existing stock of similar references, including products from the same family, was analyzed. The checks revealed that the issue of hole positioning relative to the X and Z axes also occurs in these parts. Thus, it was confirmed that the nonconformity is not isolated to the complained batch but has a broader scope, affecting other similar parts in stock.

This finding led to the extension of the analysis to products manufactured during the same period, as well as to those that went through the same processing flow, to prevent the recurrence of the same deviations in production. Relevant information is documented in Table 5.

Table 5. Immediate checking action.

D2. Immediate Checking Action			
Are There Other Similar Products Involved?			
Can this Defect Also Appear on Other Similar Parts?			
	YES	NO	Comments
Other parts		X	
Products from the same family	X		Stocks of similar references were analyzed, and it was found that the problem also occurs in these.
Left/Right		X	
Symmetrical products		X	
Front/Rear		X	
Others		X	

The system sends notifications to the members involved in the verification process to carry out immediate verification actions. Depending on the input module and the LLC component, the focus is on stocks produced during the same period as stocks produced in previous periods that went through the same processing flow. Using our solution and video cameras, the affected stocks can be monitored in the warehouse in case of nonconformity.

D3—Initial analysis

Following an initial analysis of the production flow, the moment at which the nonconformity should have been detected was evaluated. According to the available information, deviations in hole positioning could have been identified both during the manufacturing process and at the final inspection stage of the finished product, or prior to delivery.

However, the conducted checks showed that hole positioning was not included in the list of characteristics controlled at these stages. Thus, although there were multiple control points where the deviation could have been observed, the lack of a specific check for this characteristic allowed the nonconforming parts to go undetected throughout the process until shipment to the customer.

This omission led to the failure to detect the nonconformity at an early stage, which caused a negative impact on the final product quality and resulted in the complaint received. Relevant information is presented in Table 6.

Table 6. Initial analysis.

D3. Initial Analysis		
At What Stage of the Manufacturing Process Should the Nonconformity Have Been Detected?	YES	NO
During the manufacturing process	x	
On the finished product (e.g., Control Plan)	x	
Before delivery	x	
What are the reasons why it was not detected?		
Verification means allowing nonconforming parts to pass.		

Our solution makes a comparison with the verification procedure library. A comparison can be made between the key components identified by the LLM and the verification procedure libraries for the processes identified in D1. In this way, it is possible to determine when a verification procedure has not been identified.

D4—Immediate action plan

To prevent the delivery of nonconforming products to the customer, immediate containment actions were implemented through dimensional inspection of existing stocks (Table 7), both in the manufacturing process and in intermediate and final inventories.

Table 7. Immediate action plan.

D4. Immediate Action Plan			
What actions have been taken to prevent the delivery of nonconforming products to the customer?			
	Actions	Conforming quantity	Nonconforming quantity
In the manufacturing process	Stock sorting		300
Warehouse stock	Stock sorting		500
Spare parts	Not applicable		0
How are the conforming products identified?			
By verification using 3D control.			
Delivery date	Not delivered/production stopped.		
Remarks	Not delivered/production stopped.		

Specifically, the following actions were initiated:

- In the manufacturing process, parts in the production flow were sorted, resulting in 300 nonconforming parts;
- In warehouse stock, existing parts were analyzed, and 500 nonconforming parts were isolated;
- Spare parts are not applicable as they were not involved in this situation.

The identification of conforming parts is performed using 3D inspection, which allows for precise measurement of hole positioning relative to the X and Z axes, in accordance with the requirements of the technical documentation.

As a result of these measures, delivery to the customer was halted, and production was suspended until the necessary corrective actions were implemented.

D5—Final analysis

The final analysis was carried out on 25 March 2025, aiming to identify the root causes that led to the occurrence of nonconformities, taking into account the entire manufacturing process. All relevant aspects were analyzed, following the 5W1H principle (Who, Where When, Why, How), as well as possible influences from factors such as: personnel, material, machine, and methods.

Based on the conducted investigation, the following causes were identified:

- The inspection tools allow nonconforming parts to pass, as the templates for dimensional verification are incorrectly designed;
- The working method used does not ensure repeatability in execution, generating variations in hole positioning;
- The work instructions are not sufficiently clear or well-defined, leaving room for interpretation during execution;
- The measurement method is not clearly established or standardized, resulting in inconsistency in inspections;
- The laser equipment used for measurements is not properly calibrated, affecting measurement accuracy.

The results of this analysis, presented in Table 8, show that nonconformity is the result of combined deficiencies in technical, operational, and control areas, requiring structured corrective actions to eliminate the causes and prevent the recurrence of the problem.

The solution proposes the use of IoT equipment for non-invasive data acquisition from both production tools and measuring instruments. These allow for the creation of a real-time history for the respective production/measuring process. Thus, in our solution, flexible and portable methods have been implemented for connecting IoT to production equipment—measuring the power consumption of the AC motors involved in the production process, as well as optical solutions (cameras) for determining the measurement points of the equipment using LASER. All this data was collected over a time span of one year of pilot operation.

The association of the LLC with the reporting engine allows for the introduction of the actual causes across the entire process into the LLC system for generating Ishikawa diagrams (Figure 9) used to represent cause and effect in industrial process analysis, defect prevention, and product design processes [25].

D6—Final action plan

The final action plan, once developed, is also entered into our system. In this way, a complete 8D library is created—including the complaint, production and measurement history, and the action plan. This can be viewed as a digital model of the respective process, including any actual issues that have occurred.

To prevent the recurrence of the identified nonconformity, starting on 26 March 2025, a permanent corrective action plan was implemented focused on securing the process, increasing repeatability, and clarifying control methods. The actions were carried out with the aim of eliminating the causes identified in the final analysis and ensuring the consistent production of conforming products.

Table 8. Final analysis.

D5. Final Analysis	Analysis Date:	25 March 2025
Indicate the real causes across the process:		
• Labor (Man), Material, Machine, Methods, Inspection means, Management, and Environment • Who, Where, When, Why, How • Changes in the Manufacturing process, Retouch processes, Maintenance		
Causes	Responsible	Department
Verification means allowing nonconforming parts to pass. The dimensional inspection gauges/checking jigs are incorrectly designed.	Method Specialist	Technical
The work procedure used does not guarantee process repeatability.	Method Specialist	Technical
Contamination of the positioning device supports residues.	Production Responsible	Production
The measurement method is not clearly defined.	Quality Analyst	Quality
The laser system shows nonconforming calibration with the specified operational parameters.	Method Specialist	Technical
The laser system's clamping devices do not ensure effective immobilization of the part during the cutting process along the X and Z axes.	Method Specialist	Technical
The operator does not have the necessary qualifications and has not received adequate training for proper equipment operation.	Training Responsible	Training
Improper positioning of the parts in the clamping device, caused by the lack of experience and skill of the new operator.	Training Responsible	Training
The locking elements related to the X and Z axes show deformations in the upper area.	Method Specialist	Technical

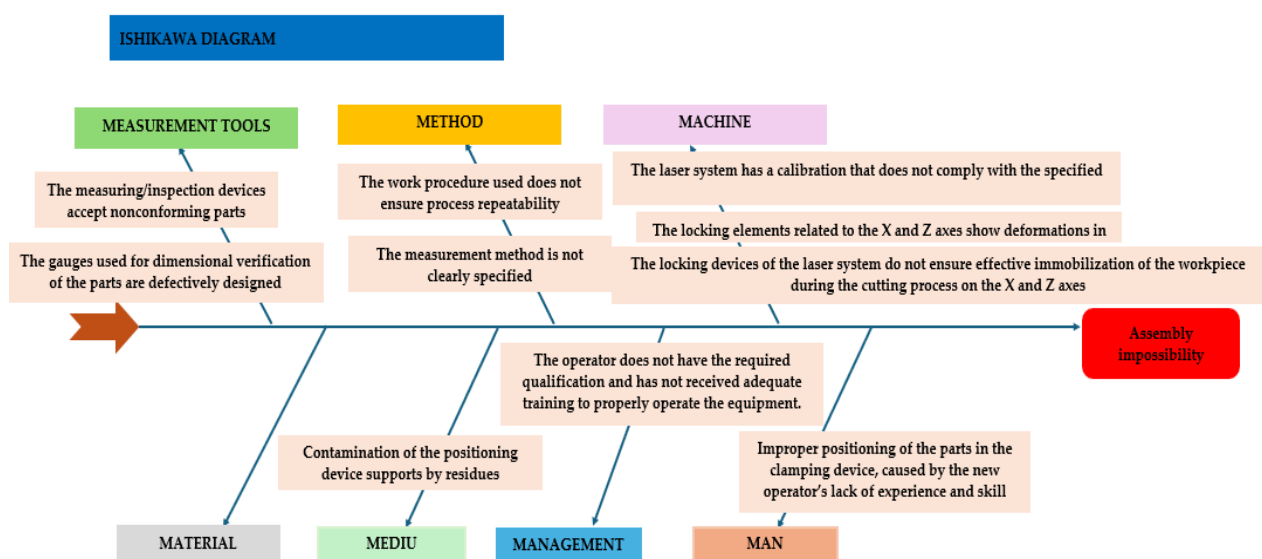


Figure 9. Ishikawa Diagram.

All planned actions were completed on schedule, during week 13 (W13), as detailed in Table 9. These measures are aimed not only at correcting existing problems but also at establishing a robust framework to prevent similar situations from occurring in the future.

Table 9. Final action plan.

D6. Final Action Plan	Application Date:			26 March 2025
What actions have been implemented to prevent the future manufacturing of nonconforming products? (securing, Poka Yoke, process control, ...)				
Action	Responsible	Department	Planned Date	Completion Date
Creation of a jig for checking hole positions (attributive)	Method Specialist	Technical	W13	W13
Manufacturing and integration of machined blocks to ensure limitation and repeatability of positioning along the Z axis	Method Specialist	Technical	W13	W13
Calibration and verification of the dimensional inspection device.	Quality Analyst	Quality	W13	W13

D7—Action plan confirmation

On 31 March 2025, the effectiveness of the actions taken was verified through an 8D audit, aimed at assessing the impact of the implemented corrective measures on the manufacturing process and checking the conformity of the products according to Table 10.

Table 10. Action plan confirmation.

D7. Action Plan Confirmation	Date:	31 March 2025	
Have the actions taken been confirmed as effective?		Yes	No
		x	
How?			
8D Audit			
Attach evidence such as dimensional reports, capability results, attribute inspection reports, ... to this document.			

Based on the audit, it was confirmed that the actions undertaken were effective and brought significant improvements to the process, and that subsequently manufactured products no longer show deviations in hole positioning relative to the X and Z axes. The verification of the effectiveness of the actions was carried out through the following activity.

The 8D audit was conducted to systematically evaluate the effectiveness of all corrective measures that had been implemented. The audit confirmed that each action taken successfully addressed the identified nonconformities and prevented their recurrence. All supporting evidence is compiled in Table 11, which provides a detailed overview of the corrective measures applied, the corresponding outcomes, and the observed improvements in process quality.

This comprehensive assessment demonstrates the reliability and robustness of the implemented solution, reinforcing its value in enhancing overall quality management within the production process.

In D7, IoT devices were also used for real-time data acquisition during production and measurements. Thus, along with the data collected during the production process that contained non-conformities, we also have the data collected during the application and confirmation of the final action plan and the audit. At the same time, the procedure

library is updated with the verification procedures applied to prevent the recurrence of non-conformities—D8.

D8—Prevention of problem recurrence.

Table 11. 8D Audit.

Date: 31 March 2025 Prepared by: Alexandru OANCEA Department: Quality		Nonconformity: Positioning Deviations of the Holes in Relation to the X and Z Axes Compared to the Nominal Values Specified in the Technical Documentation		
Subject: 8D Follow-up Audit Status Following CUSTOMER/INTERNAL Complaint				
Expected: Validation of the action plan with due date as of the 8D audit.				
No.	Action	Completion Percentage (%)	Closing Date	Responsible
1	Creation of a jig for checking hole positions (attributive)	100%	Week 13	Technical
2	Manufacturing and integration of machined blocks to ensure limitation and repeatability of positioning along the Z axis	100%	Week 13	Technical
3	Calibration and verification of the dimensional inspection device	100%	Week 13	Quality

Following the completion of the nonconformity correction process, a set of preventive actions was established and implemented to prevent the recurrence of the identified issues. These measures aim to enhance internal processes, provide targeted personnel training, and strengthen quality control procedures (see Table 12).

Table 12. Prevention of problem recurrence.

D8. Prevention of Problem Recurrence	Closing Date	31 March 2025		
	Yes/No	Responsible	Department	Deadline
Internal training sheets	Yes	Method Specialist	Technical	W14
Manufacturing ranges	Yes	Method Specialist	Technical	W14
Control plans, control charts	Yes	Quality Engineer	Quality	W15
FMEA/AMDEC	Yes	Pilot FMEA	Quality	W16
Lesson learned	No			
Plans	No			
Inspection tools, gauges	Yes	Method Specialist	Technical	W15
Others	No			
Supplier follow-up	No			

The implementation of these preventive actions ensures that potential deviations are addressed proactively, reducing the likelihood of future nonconformities and improving overall product quality. The target date for the full implementation of all preventive measures is 31 March 2025, allowing sufficient time for proper integration and verification within the production system.

In this process, the LLC component is utilized to systematically generate key documentation that supports the 8D problem-solving methodology. This includes the preparation of

the FMEA, which identifies potential failure modes and evaluates their impact on the product or process. Additionally, a comprehensive control plan is developed to ensure that all critical parameters are monitored and controlled during production. Action plans are also prepared to outline the steps required to implement corrective and preventive measures effectively. Finally, internal training sheets are generated to provide structured guidance and instructions for personnel, ensuring consistent application of quality procedures and promoting continuous improvement within the organization.

4.3. Presentation of the Solution

Our proposed solution for implementing 8D is presented in the block diagram in the figure below.

The solution is composed of three modules—shown centrally in Figure 10:

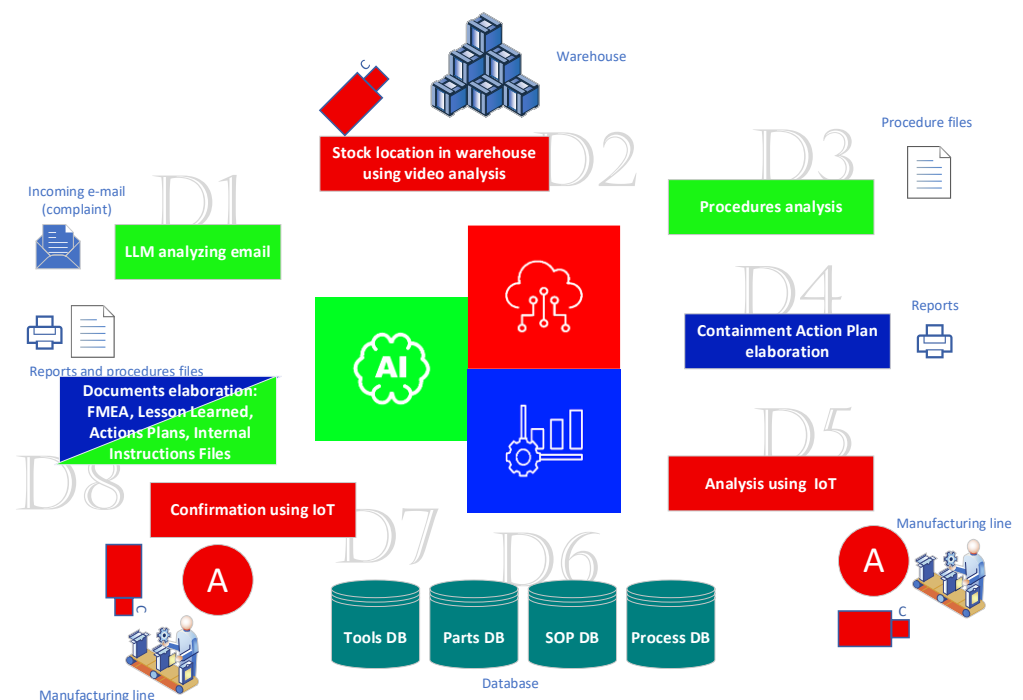


Figure 10. Block diagram of the solution. Letter A comes from Ampere—represents sensors used to measures the current consumption, letter C comes from Camera—used for parts analysis and detection.

The AI module (green), which consists of a Large Language Model component capable of analyzing emails and procedure files and extracting from them the information needed for intelligent analysis.

The IoT module (red), composed of a Complex Event Processing component that collects data from IoT modules, analyzes it, and stores it. In our case, the IoT components consist of video cameras and circuits that measure power consumption. The video cameras capture images and send them to the IoT module, where the images are analyzed and the components of interest are extracted. A detailed description of the module is provided in the next section. The circuits that measure power consumption are non-invasive measuring solutions placed on the cable (without any invasive intervention on the cable) to determine the current consumption. This is then sent to the IoT module, where it is analyzed and stored.

The Reports Engine module (blue), which generates reports (printable files) based on input data. The input data comes either from the AI module after analysis or from the database where it has been stored.

The three modules are implemented using different technologies. The LLM AI module is essentially an interface based on a Python library (OpenAI) (v 3.12) connected to the most well-known and advanced LLM tool—ChatGPT (GPT 5). For the pilot used in this case study, the latest version of ChatGPT-5 was used and for fault identification and keyword extraction, a simple prompting without additional training was used. Any future developments involving the extension of the framework to other cases (other production processes, other industry domains) will also involve additional configuration of the LLM tool. The IoT module is based on a Complex Event Processing component from the open-source WSO2 solution, specialized in creating data processing flows from IoT components, as well as on a video analysis module built using the OpenCV library in Python. WSO 2 is used to extract emails (email connector), assemble them into a simple prompt and send them to LLM. The assembly is performed by using fixed expressions like “extract the keywords that identify defects and the production process from the following text: <email content>”. Expressions like: “extract the keywords that identify defects from the production process <process name> from the following text: <email content>” using the <process name> returned by the first expression are also formulated. Finally, the reports module is based on the Jasper Reports engine, capable of automatically generating reports based on the report parameters (type, page layout, table layout, etc.) and input data—retrieved directly from data collections or passed as parameters. The AI module, the IOT module (WSO2) and the Reports Engine module run on a server where they communicate with each other via REST. Communication at the AI module level with LLM is also performed via the REST-API existing in the Python library.

The solution also integrates IoT hardware components used in different phases of the 8D analysis: video cameras and power consumption measurement circuits. The video cameras are used in several phases:

- As equipment for detecting containers storing parts in the warehouse. The camera is positioned so that it can detect the labels on the storage containers of finished parts in the warehouse. In this way, the camera can continuously send images from the warehouse to the video analysis module. Here, the labels are extracted from these images, and the containers are identified. This allows the video analysis module to provide the location of the container with the parts of interest—enabling quick localization.
- As equipment that captures images from the production process. These images are also sent to the video analysis module. Here, an operation is performed to identify the position of the holes and the shape of the part. The analysis extracts this data and stores it for defect identification or for identifying the corrections applied by the action plan.

In both cases, the scenario is the same: the camera captures images that are then sent to the intelligent video analysis module. Here, the image is analyzed, and useful data is extracted from it: the position of the container, the position of the marked points, and the conformity of the part.

The video cameras transmit the information to the server Via the existing ethernet infrastructure. The IoT modules for measuring current consumption (illustrated with the letter A in Figure 10) communicate the information to a data collector using the free 866 MHz radio band and from there through the existing ethernet infrastructure the data also reaches the server.

The diagram also illustrates the operations that our solution performs for all 8D stages. Around the edges of the figure, the stages of the 8D analysis are represented using letters and numbers, while the colored rectangles indicate the operation performed by our solution. The legend of the solution modules that perform the operation has been kept for the rectangles: green for operations performed by the AI module, red for operations

performed by the IoT module, and blue for operations performed by the report generator. The exception is stage D8, where both green and blue are used, as this stage involves both the AI module and the Report Engine module.

Below, we present the 8D stages along with the operations carried out at each stage by our implemented solution:

D1—Issue details—The solution provides an email analysis module for received emails. This consists of a connector that receives emails and an AI LLM component that automatically identifies in the email the keywords referring to a complaint and the type of product/process to which the complaint relates.

Advantages: reduced analysis time when receiving a complaint and automatic input of complaint-related data into the system. The first advantage is rather hypothetical in our implementation—in our case study, a single operator receiving the emails could perform the same task at the same speed. However, issues were recorded in entering the data into the system and in convening the parties involved in resolving the problem. Thus, with our solution, the execution time for D1 was reduced from hours to less than one minute (time to send notifications to parties Via ethernet—10–20 s).

D2—Immediate checking actions—Based on the data collected in stage D1, the solution enables the immediate notification of the parties involved. Stocks produced during the same period, as well as those produced in previous periods and currently in the warehouse, are identified immediately (reaction time of less than one minute from complaint receipt). Using the intelligent image analysis module connected to the two cameras placed in the warehouse, the containers with parts that may have issues are also located instantly. **Advantages:** the time to notify the parties involved in the issue, as well as the time to identify the affected stocks, is reduced to less than one minute (analyze time to obtain container number: 20–30 s; signaling to the server; 5–10 s).

D3—Initial analysis—The LLM module extracts from the complaint the keywords that are then used for the automatic search of verification procedures for the identified processes. In this way, all the data needed to detect the absence of a verification procedure is made available to the parties involved (quality team, production engineers). **Advantages:** our proposed solution reduces the D3 analysis time to less than one minute (analysis time 1–5 s).

D4—Immediate action plan—The immediate actions focus on stopping production processes and sorting nonconforming parts. Here, our solution provides the capability to synthesize the immediate action plan—the document on which the immediate measures are based. **Advantages:** an observation made from analyzing the 8D procedures applied before implementing the solution presented in this paper was related to the long time required to generate documents. By using a report engine (the blue module represented in the figure), the time needed to generate documents has been significantly reduced—to just a few seconds. Our report generation module has a template that allows for the editing of the layout of the information in the report, as well as for the automatic retrieval of data.

D5—Final analysis—In our solution, non-invasive data acquisition directly from manufacturing equipment is possible, enabling real-time monitoring of the machines. In our case, we use video cameras and intelligent image analysis to observe how holes are generated in the part and the measurement points of the equipment using LASER, as well as power consumption measurement circuits that determine the operating mode of the equipment. All this information is acquired, analyzed, and stored. **Advantages:** before implementing our solution, a major issue was the collection of data from equipment. In our solution, this is addressed by placing IoT acquisition modules and using on-server analysis modules.

D6—Final action plan—Our solution allows for the storing in databases of all the data acquired in the previous steps. This creates a complete picture of the process and the

problem that occurred. Advantages: by using AI, scenarios associated with the current complaint can be easily searched later, and possible scenarios of other problems that may arise, along with ways to respond to them, can also be generated.

D7—Action plan confirmation—Our solution enables the evaluation of the action plan's impact by monitoring in real time the equipment involved in the production process. In the case study presented in this paper, the two types of IoT systems used for data acquisition are video cameras (2) and power consumption measurement circuits (2). Advantages: the information acquired here is also stored in databases, from which complete scenarios of failures and corresponding responses can later be developed.

D8—Prevention of problem recurrence—This stage involves the possibility of repeating the scenario with possible variations and preparing the final documents: FMEA, lessons learned plan, action plan, and internal training sheets. Advantages: all the documents that need to be generated in this stage are synthesized by our report engine in just a few minutes.

4.4. Implementation of Corrective Actions

To identify the causes that led to deviations in hole positioning along the X and Z axes, a detailed analysis of the inspection reports for the batches reported by the customer was conducted. The obtained results confirmed the reported nonconformities: the hole positioning shows deviations from the nominal values specified in the technical documentation, with some cases exceeding the allowable tolerance limits. These deviations negatively impacted assembly conformity, affecting the assembly process and the final product functionality.

The initial findings were supported by internal measurements and inspection documents provided by the customer.

During the analysis, several potential causes were identified that could have contributed, directly or indirectly, to the positioning deviations. These include the promotion of nonconforming parts by the inspection tools due to incorrectly designed dimensional control gauge, as well as the existence of a working procedure that does not ensure sufficient process repeatability. Additionally, contamination of the supports in the positioning device with process residues was observed, which can affect part stability during machining.

Operational factors were also noted: the lack of a clearly defined measurement method, deviations in laser system calibration relative to specified parameters, and inefficient part clamping during processing on the X and Z axes. Furthermore, deficiencies in operator training, along with incorrect part placement in the device due to lack of practical experience, were identified. Another issue was deformation of the locking elements for the X and Z axes, especially in the upper area, which further contributed to instability during positioning.

Among all these causes, this study will primarily address those considered to have a direct and immediate impact on part positioning: deviations in the machining program, fixture clamping and adjustment, as well as calibration of the inspection system and laser equipment.

4.4.1. Analysis of Nonconforming Parts—Measured Results

To confirm the positioning deviations, dimensional measurements were performed on a sample of three nonconforming parts, taken from the batches reported by the customer. The measurements were carried out using the FARO Prime 3D probing arm (manufactured by FARO Europe GmbH & Co. KG, with its main center in Korntal-Münchingen, Germany) with a working range of 3700 mm, used for precise verification of geometric features in large-sized parts (Figure 11).



Figure 11. FARO Prime 3D Arm.

This step aimed to determine the exact positional deviations of the holes relative to the nominal values specified in the engineering drawing, particularly along the X and Z axes, for the analyzed parts. The obtained results confirmed the existence of deviations, supporting the initial findings and highlighting the repetitive nature of the nonconformity.

The notations used are as follows:

- dx—direction along X;
- dz—direction along Z;
- dx/S or D—direction along X, left or right;
- dz/S or D—direction along Z, left or right.

Table 13 presents a summary of the measured values for each analyzed part, compared to the technical specifications.

Table 13. Summary of measured values.

Axis	Nominal	Lower Tolerance	Upper Tolerance	Measured Part 1	Measured Part 2	Measured Part 3	Maximum Deviation
dx	1722.1	−0.8	+0.8	1720.479	1720.89	1720.973	−1.621
dz	136.335	−0.8	+0.8	136.335	136.358	136.346	−0.165
dx	1624.4	−0.8	+0.8	1622.794	1623.159	1623.285	−1.606
dz	206.8	−0.8	+0.8	206.669	206.363	206.692	−0.164
dx	199.6	−0.8	+0.8	198.222	198.594	198.733	−1.378
dz	206.8	−0.8	+0.8	206.8	206.621	206.668	−0.179
dx	101.9	−0.8	+0.8	100.567	100.914	101.062	−1.333
dz	136.5	−0.8	+0.8	136.41	136.306	136.362	−0.986

Table 13. Cont.

Axis	Nominal	Lower Tolerance	Upper Tolerance	Measured Part 1	Measured Part 2	Measured Part 3	Maximum Deviation
dx	11	−1	+1	11.23	11.228	11.237	0.237
dx	13	−1	+1	13.324	13.281	13.296	0.296
dz/S	7	−1	+1	7.257	7.177	7.221	0.257
dx/D	7	−1	+1	7.234	7.286	7.179	0.286
dz	103.4	−1	+1	103.09	103.09	103.196	−0.310
dx	110.2	−1	+1	109.874	109.86	109.919	−0.340
dz	42.6	−1	+1	41.711	41.668	41.818	−0.932
dx	55.8	−1	+1	56.882	55.902	56.96	1.160
	45	−1	+1	45.119	45.15	45.221	0.221
	15	−1	+1	14.658	14.554	14.612	−0.342
	15	−1	+1	15.338	15.252	15.224	0.224
	45	−1	+1	45.19	45.321	45.37	0.370
	0	0	+2	0.744	0.834	0.646	0.834
	0	0	1	0.118	0.083	0.176	0.176
dx	877	−0.8	+0.8	876.425	876.772	876.989	−0.575
dx	70	−0.5	+0.5	69.997	69.973	70.283	0.283
dz	37	−0.8	+0.8	36.887	37.129	37.333	0.333
dx	1824	−1.5	+2.5	1823.097	1824.587	1823.494	−0.913
dx	40.4	−0.8	+0.8	39.951	40.418	40.535	−0.449
dz	19	−0.8	+0.8	19.467	19.229	19.32	0.467
dx	89.7	−0.8	+0.8	89.269	89.658	89.714	−0.431
dz	104.3	−0.8	+0.8	104.782	104.895	104.776	0.595
dx	170.3	−0.8	+0.8	169.688	170.099	170	−0.612
dz	199	−0.8	+0.8	198.841	198.91	199.08	−0.159
dx	229.3	−0.8	+0.8	228.905	229.189	229.337	−0.395
dz	214.8	−0.8	+0.8	214.353	214.773	214.947	−0.447
dx	339.634	−0.8	+0.8	339.634	340.078	340.191	−0.766
dz	244.184	−0.8	+0.8	244.5	244.376	244.462	−0.316
dx	517.4	−0.8	+0.8	516.882	517.358	517.437	−0.518
dz	292	−0.8	+0.8	291.347	219.367	291.349	−0.653
dx	567.9	−0.8	+0.8	567.457	567.756	568.157	−0.443
dz	305.5	−0.8	+0.8	304.678	304.645	304.965	−0.822
dx	712	−0.8	+0.8	711.431	711.958	712.035	−0.569
dz	321.8	−0.8	+0.8	320.9	321.184	321.135	−0.900
dx	712	−0.8	+0.8	711.431	711.958	712.035	−0.569
dz	321.8	−0.8	+0.8	320.9	321.184	321.135	−0.9
dx	833.6	−0.8	+0.8	833.172	833.874	833.455	−0.145
dz	350	−0.8	+0.8	324.232	324.466	323.994	−1.006

Table 13. Cont.

Axis	Nominal	Lower Tolerance	Upper Tolerance	Measured Part 1	Measured Part 2	Measured Part 3	Maximum Deviation
dx	990.4	−0.8	+0.8	990.148	990.599	990.817	0.199
dz	325	−0.8	+0.8	324.475	323.96	323.994	−1.006
dx	1653.3	−0.8	+0.8	1652.786	1635.18	1653.135	−0.12
dz	199	−0.8	+0.8	198.503	197.575	197.714	−0.1425
dx	1594.7	−0.8	+0.8	1594.29	1594.422	1594.6	−0.278
dz	214.8	−0.8	+0.8	213.884	213.343	213.447	−1.366
dx	1483.7	−0.8	+0.8	1482.973	1483.437	1483.506	−0.263
dz	244.5	−0.8	+0.8	243.876	243.165	243.345	−1.335
dx	1306.6	−0.8	+0.8	1306.053	1306.6	1306.418	−0.182
dz	292	−0.8	+0.8	291.238	290.91	290.82	−1.18
dx	1112	−0.8	+0.8	1111.483	1111.75	1111.871	−0.25
dz	321	−0.8	+0.8	321.003	320.492	320.678	−1.35
dx	1256.1	−0.8	+0.8	1255.515	1256.06	1256.009	−0.04
dz	305	−0.8	+0.8	304.813	304.342	304.453	−1.258
dz/S	345	−1	+1	344.312	344.504	344.89	−0.498
dz/D	345	−1	+1	344.026	344.248	344.08	−0.92
dz	5	−1	+1	4.922	4.815	4.852	−0.185
dz	5	−1	+1	5.107	5.047	5.029	0.047
dz	12	−1	+1	11.613	11.704	11.623	−0.387
dz	12	−1	+1	11.691	11.759	11.722	−0.309
dz	17.1	−1	+1	16.838	17.207	17.302	−0.262
dz	17.1	−1	+1	17.196	18.167	16.989	1.067

Values indicated in red are outside the tolerance range.

4.4.2. Manufacturing and Integration of Machined Blocks to Ensure Repeatability of Positioning on the X and Z Axis

To correct the positioning deviations identified on the X and Z axis, a corrective action was implemented to optimize the clamping device used in the machining process (Figure 12). The initial analysis revealed that the existing guiding and support elements—centering assemblies previously mounted in the device—did not provide a clear and repeatable limitation of the part's position along the vertical axis. The centering assemblies previously mounted in the device are highlighted with a red frame in Figure 13.

These components exhibited assembly play and early wear, which led to variable part positioning from one cycle to another.

The centering assemblies previously used consisted of a set of components that, although functional during the initial operational phase, proved to be ineffective in maintaining stable and repeatable positioning over time. The structural complexity of these assemblies contributed to internal play, alignment difficulties, and more challenging maintenance.

Based on the obtained data, an inspection report of the fixture was generated, highlighting discrepancies between the measured values and the references from the engineering documentation. These findings supported the conclusion that the previously used centering assemblies did not ensure consistent positioning from one cycle to another. The report generated is in graphical form and is illustrated in Figure 14.

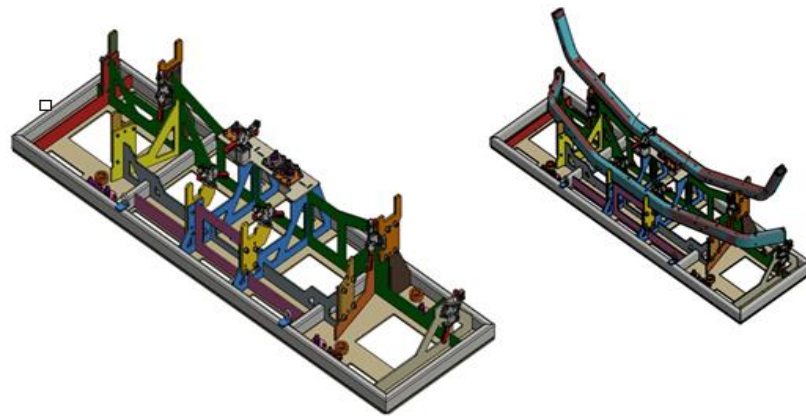


Figure 12. Positioning device.

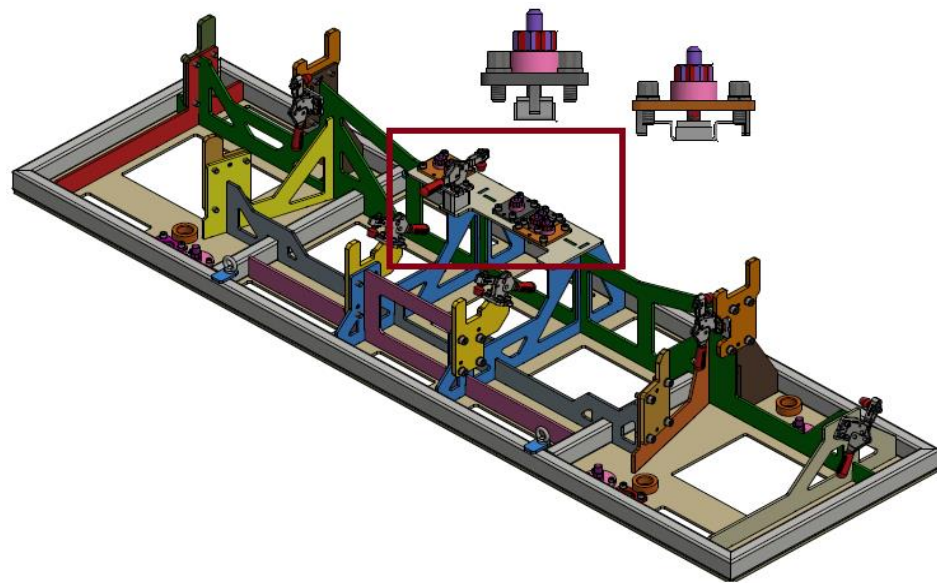


Figure 13. Centering assemblies on the device. With red is represented what is not comply with quality standards—the fault.

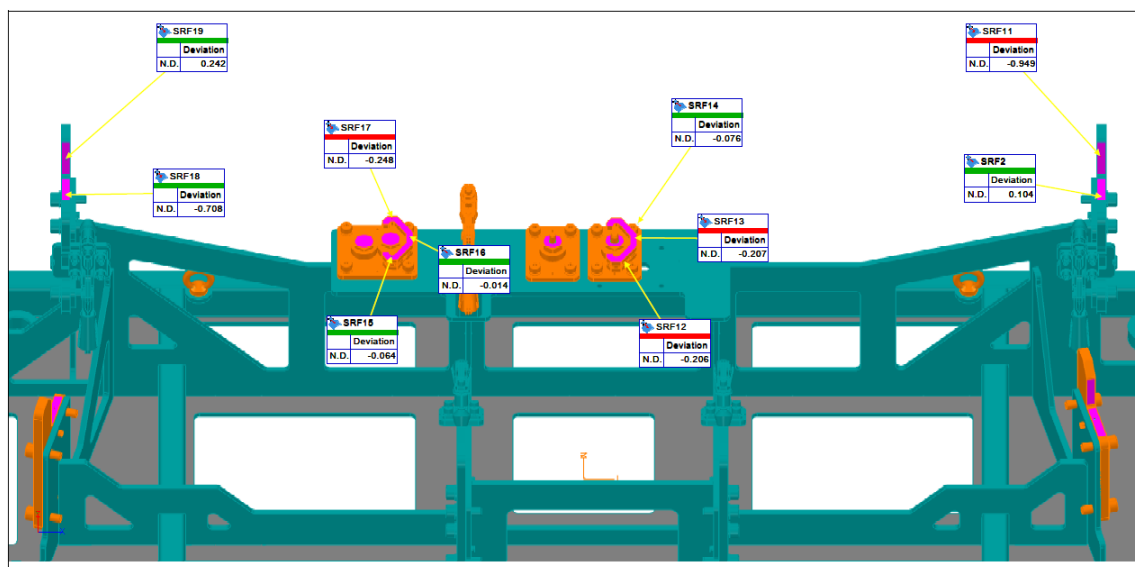


Figure 14. Three-dimensional inspection report—centering assemblies.

To address this issue, new centering assemblies were designed and manufactured, consisting of machine blocks indicated by the green frame in Figure 15.

The elements were designed to provide rigid support for the part along the X, Z axis, thereby eliminating any possibility of undesired movement during clamping.

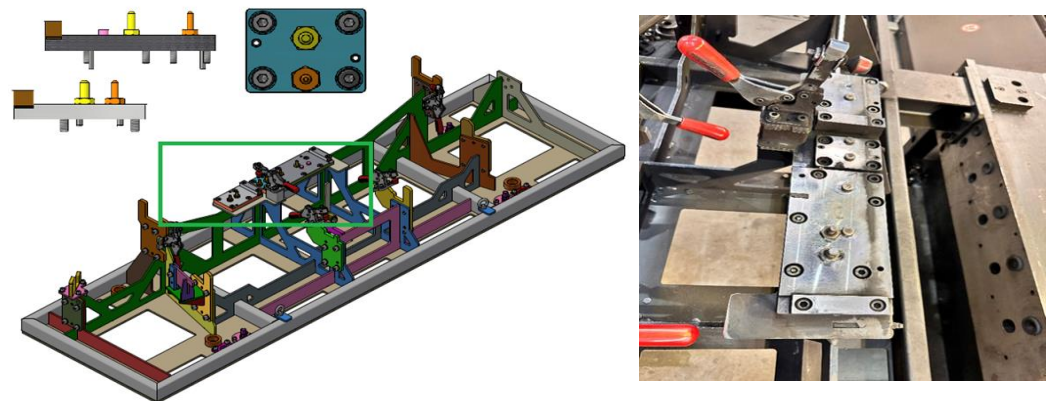


Figure 15. Centering assemblies made from machined blocks. With green is represented the correction which solves the fault.

Their integration into the clamping device assembly aims to ensure precise and repeatable positioning, regardless of potential dimensional variations in the semifinished parts. The centering assemblies are additionally equipped with a Poka-Yoke bolt, intended to prevent incorrect installation of the part in the device.

This design solution significantly contributes to improving machining process accuracy and reducing nonconformities caused by incorrect positioning.

To validate the conformity of the machine blocks, they were inspected directly on the cutting device under real assembly conditions. Adjustments were made to ensure that the contact areas complied with the dimensional and geometric tolerances specified in the design, providing stable positioning along the X and Z axis. The results confirmed that the deviations were within the allowable limits, and the conformity of the machined centering assemblies was documented in a 3D inspection report, shown in Figure 16.

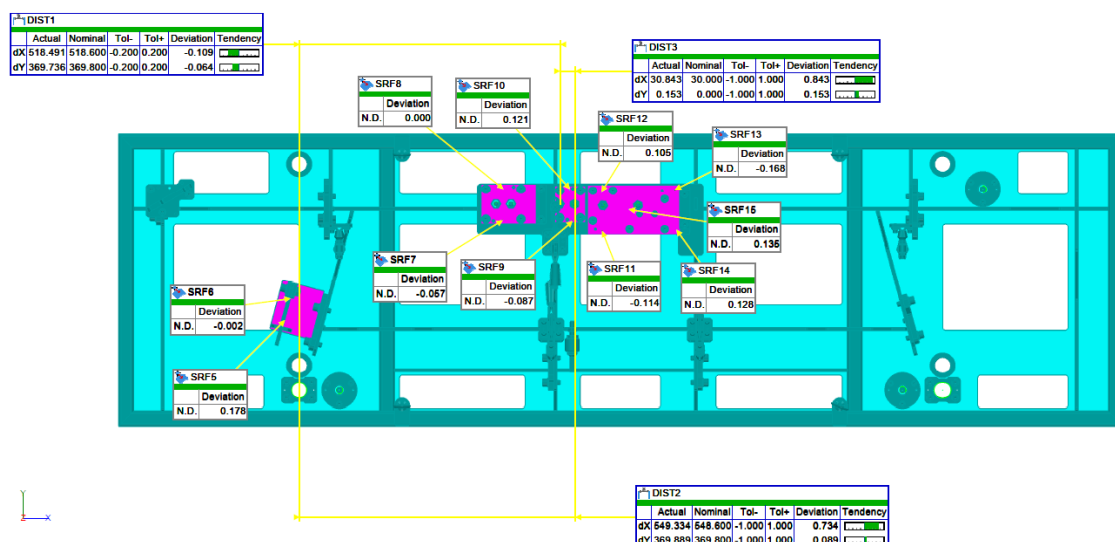


Figure 16. Three-dimensional report confirming position of centering assemblies—machined blocks.

4.4.3. Calibration and Verification of the Fixture for Dimensional Inspection

The device used for dimensional inspection of the part operates on a “go/no-go” principle, providing an attribute-based assessment of the part’s geometric conformity

(Figure 17). In this system, the part is placed into a calibrated slot, and whether it passes or is blocked indicates if it meets the allowable tolerances for contour and positioning.

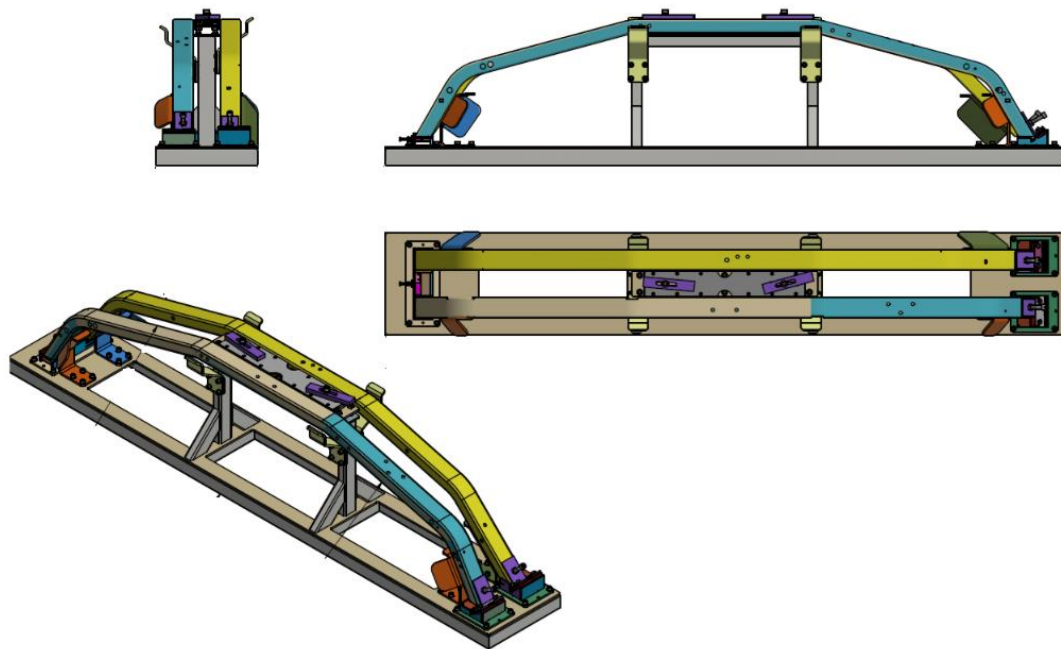


Figure 17. Device for dimensional inspection.

Following the customer complaint, an additional verification of the inspection device was carried out. The inspection report highlighted that the device did not meet all calibration standards, which led to the acceptance of nonconforming parts that were initially considered compliant (Figure 18).

Table 14 presents the dimensional deviations from the inspection report of the verification device.

Table 14. Dimensional deviations from the report.

Nominal Dimension	Lower Tolerance	Upper Tolerance	Measured Dimension
344	−0.050	+0.050	343.988
344	−0.050	+0.050	344.356
344	−0.050	+0.050	344.349
344	−0.050	+0.050	343.847
1825.3	−0.1	+0.1	1826.603
1827.66	−0.1	+0.1	1828.980

Values indicated in green are within the tolerance range; values indicated in red are outside the tolerance range.

Analysis of the values shown in Table 12 indicates that in over 80% of the measurements performed, deviations from the acceptance values were observed. The respective parts, which had been delivered to the customer, did not meet the dimensional requirements, and their nonconformities, such as incorrect hole positioning, were not detected during the initial inspection process.

Therefore, precise adjustments were made to the device components, including alignment of the mounting slot and part positioning, to strictly comply with the dimensional tolerances specified in the technical documentation.

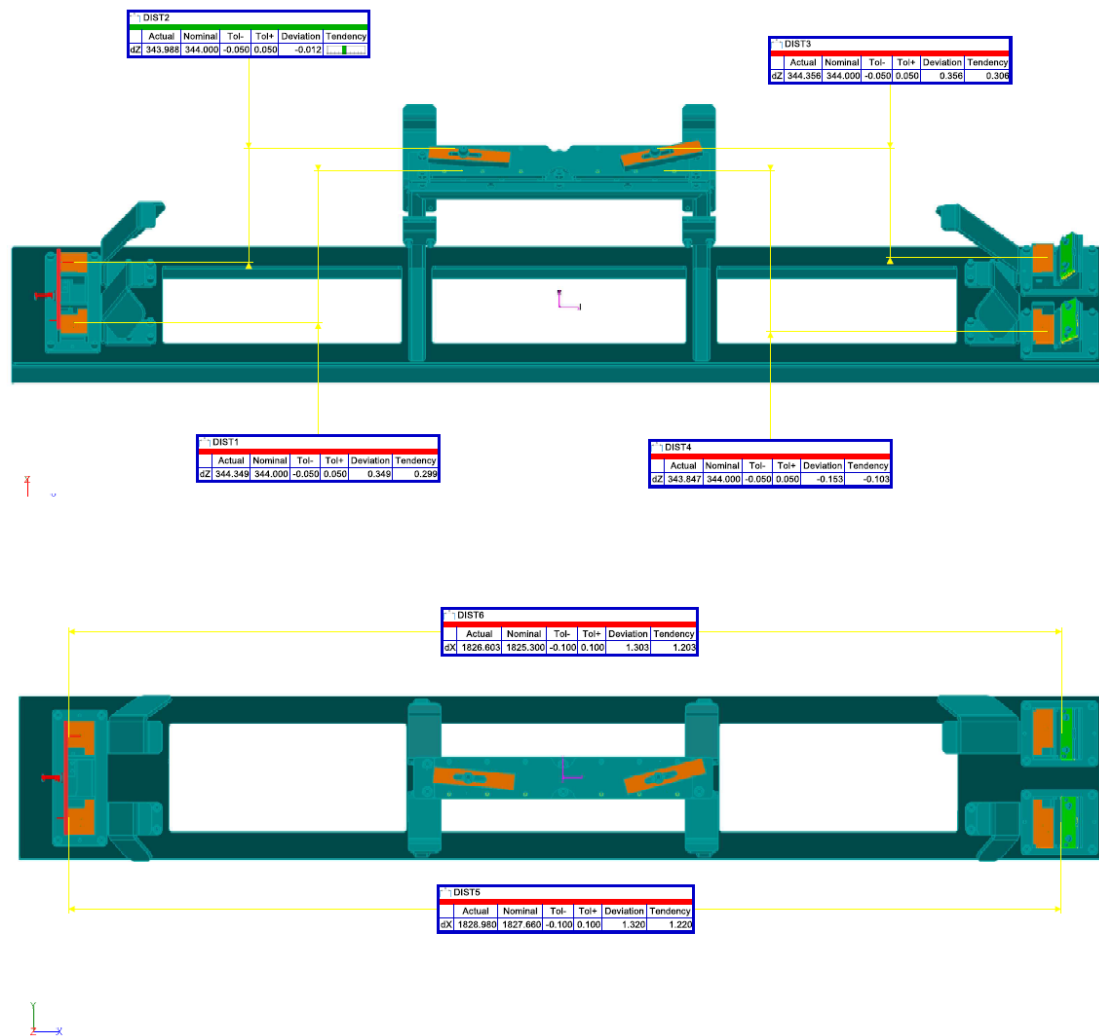


Figure 18. Inspection device report—nonconforming.

After the adjustment, the fixture was verified using a 3D probing arm, and the measurements confirmed that it now meets the technical specifications and can provide accurate results. Following the verification, a compliant report was generated, certifying the correctness of the adjustment and the conformity of the fixture with calibration requirements (Figure 19).

Thus, the inspection process was restored to optimal parameters, ensuring accurate measurements and eliminating the risk of delivering nonconforming parts.

Table 15 presents the measurement results from the inspection report of the verification device.

Table 15. Measurement results.

Nominal Dimension	Lower Tolerance	Upper Tolerance	Measured Dimension
344	−0.050	+0.050	343.988
344	−0.050	+0.050	343.997
344	−0.050	+0.050	344.047
344	−0.050	+0.050	344.039
1825.3	−0.1	+0.1	1825.314
1827.66	−0.1	+0.1	1827.569

Values indicated in green are within the tolerance range.

To validate the effectiveness of the inspection device after the performed adjustments, a statistical R&R (Repeatability & Reproducibility) analysis was conducted, according to the MSA (Measurement System Analysis) methodology. The purpose of this analysis was to evaluate the measurement system's capability to provide consistent and reproducible results, regardless of the operator or measurement cycle.

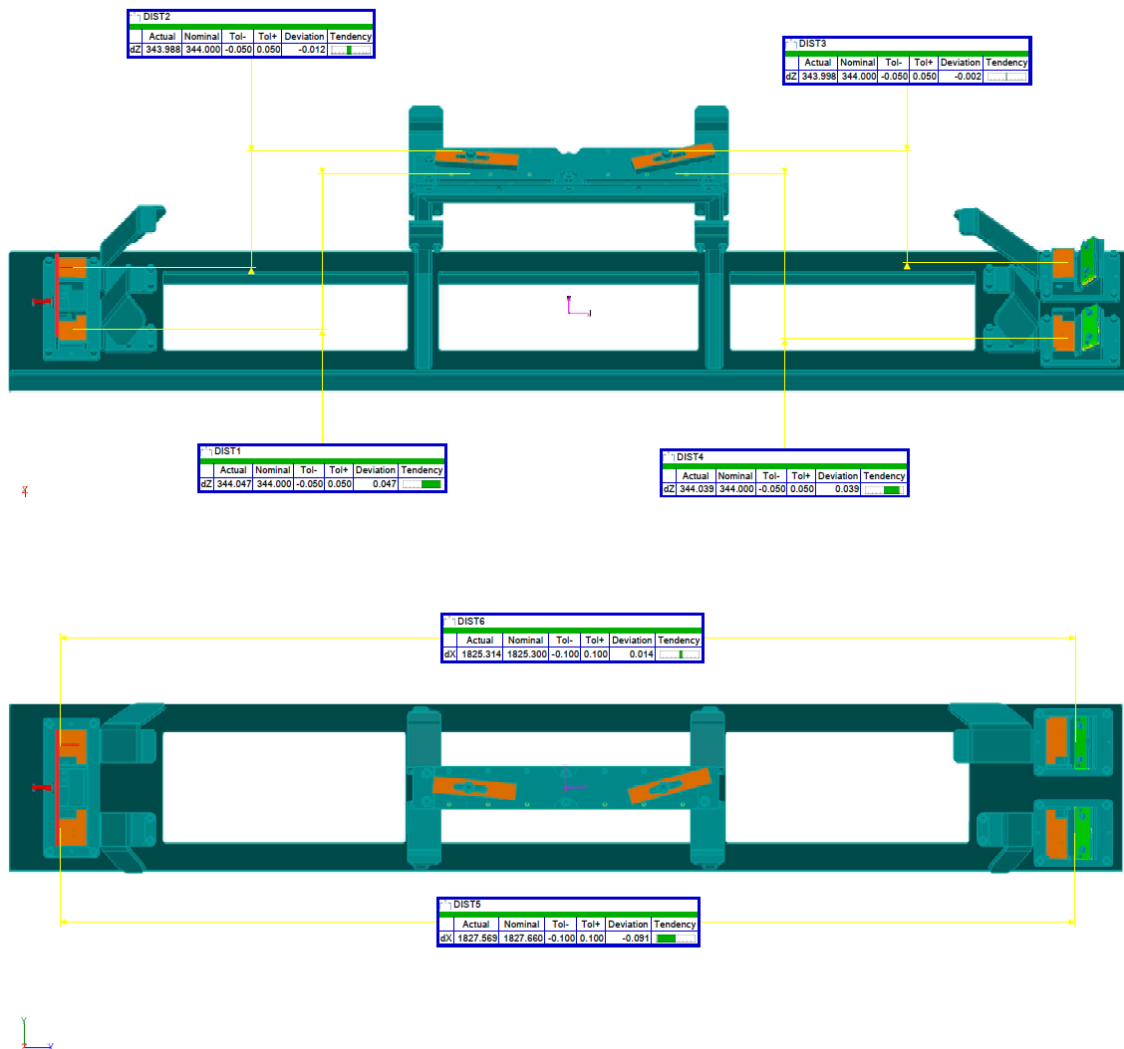


Figure 19. Inspection device control report—conforming.

The R&R analysis was attribute-based and carried out using two operators (Operator 1 and Operator 2), each performing two inspections on the same sample of 50 parts. The evaluation was based on binary criteria: C—Conforming and NC—Nonconforming, reflecting the final decision to accept or reject the part (Figure 20).

The results obtained showed that the inspection system operates efficiently, with an accuracy of over 90%. The number of nonconforming parts incorrectly classified as good was below 2%, and the number of good parts mistakenly rejected was below 5%. These values are within the limits accepted by industry standards and demonstrate that the fixture can correctly distinguish between good and defective parts, without significant influence from the operators or the measurement method. Graphic (Figure 21) illustrates the agreement between appraisers ('Within Appraisers'). The vertical red line passing through each operator represents the 95% confidence interval (CI) for the percentage of agreement or the respective measurement. The blue dot, labeled 'Percent', indicates the observed value of the agreement percentage for each operator. The red vertical line shows

the interval within which there is 95% confidence that the true agreement percentage lies, representing the uncertainty range.

	OPERATOR 1.1	OPERATOR 1.2	OPERATOR 2.1	OPERATOR 2.2
1	C	C	C	C
2	NC	NC	NC	NC
3	C	C	C	C
4	C	C	C	C
5	NC	NC	NC	NC
6	C	C	C	C
7	C	C	C	C
8	C	C	C	C
9	NC	NC	C	C
10	NC	NC	NC	NC
11	C	C	C	C
12	C	C	C	C
13	C	C	C	C
14	C	C	C	C
15	NC	NC	NC	NC
16	C	C	C	C
17	C	C	C	C
18	NC	NC	NC	NC

Figure 20. Attribute-based R&R analysis (Minitab report).

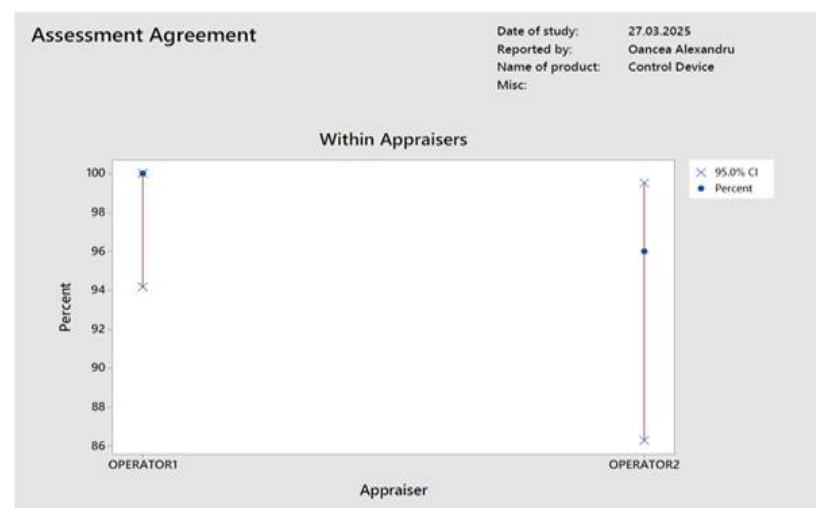


Figure 21. Graphic representation of attribute-based R&R analysis (Minitab report). Red lines represent the confidence interval (CI) for the percentage of agreement or the respective measurement.

The R&R (Repeatability and Reproducibility) analysis confirms that the inspection equipment operates in full compliance with quality requirements. It demonstrates that the measurements are consistent, reliable, and repeatable across different operators and conditions. This verification reinforces confidence in the validity of the data collected during the production process, ensuring that any deviations are accurately detected and that quality control decisions are based on trustworthy and precise measurement results.

4.4.4. Verification of Part Conformity

The modifications made to the fixture device were followed by a validation phase, during which the behavior of the parts during positioning and machining was monitored.

This testing phase included careful observation of positional repeatability and its influence on the machining process, showing a significant reduction in measured deviations. The recorded values were comfortably within the tolerance limits specified in the technical documentation, confirming the effectiveness of the implemented corrective actions.

For a concrete evaluation of conformity, a sample of 50 parts from current production was selected and inspected. The inspection was carried out using the FARO Prime 3D arm, utilizing the coordinated measurement system (CMM) to accurately determine the

hole positions relative to the X and Z axes. Control reports were generated during the measurements, and the results were summarized in Table 16, representing the minimum, average, and maximum measured dimensions.

Table 16. Summary of measurement results and process capability study.

Nominal Dimension	Lower Tolerance	Upper Tolerance	Minimum Measured Value	Average Value	Maximum Measured Value	C_pK	P_pK
1722.1	−0.8	+0.8	1721.6	1722.023	1722.28	1.62	1.64
136.335	−0.8	+0.8	136.134	136.719	136.4	1.71	1.77
1624.4	−0.8	+0.8	1624.21	1624.468	1624.78	2.14	2.07
206.8	−0.8	+0.8	206.568	206.864	207.219	1.59	1.54
199.6	−0.8	+0.8	199.234	199.591	199.94	1.77	1.72
101.9	−0.8	+0.8	101.675	101.916	102.227	1.94	1.87
136.5	−0.8	+0.8	136.067	136.513	136.956	1.48	1.58
11	−0.8	+0.8	10.773	11.013	11.232	2.41	2.15
13	−1	+1	12.635	13.009	13.488	1.46	1.55
7	−1	+1	6.662	6.971	7.428	1.63	1.74
7	−1	+1	6.620	6.965	7.378	1.79	1.73
104.3	−1	+1	103.7	104.272	104.678	1.39	1.52
110.2	−1	+1	109.739	110.198	110.59	1.85	1.89
42.6	−1	+1	42.378	42.663	43.110	1.51	1.59
55.8	−1	+1	55.435	55.808	56.154	1.61	1.69
45	−1	+1	44.468	45.001	45.403	1.73	1.66
15	−1	+1	14.622	15.002	15.461	1.55	1.63
15	−1	+1	14.590	14.996	15.459	1.71	1.62
0	0	+1	0.231	0.770	0.509	1.56	1.68
0	0	+2	0.475	0.992	1.542	1.51	1.51
877	−0.8	+0.8	876.34	876.948	877.305	1.55	1.53
70	−0.5	+0.5	69.685	69/963	70.297	1.92	1.86
37	−0.8	+0.8	36.579	37.002	37.251	1.77	1.89
1824	−1.5	+2.5	1823.41	1823.932	1824.56	1.76	1.69
40.4	−0.8	+0.8	40.0571	40.772	40.3722	1.68	1.78
19	−0.8	+0.8	18.643	18.990	19.292	1.69	1.69
89.7	−0.8	+0.8	89.379	89.722	90.005	1.86	1.74
104.3	−0.8	+0.8	103.964	104.291	104.675	1.96	1.84
170.3	−0.8	+0.8	169.985	170.598	170.263	1.76	1.70
199	−0.8	+0.8	198.571	198.997	199.311	1.62	1.69
229.3	−0.8	+0.8	228.983	229.320	229.850	1.55	1.50
214.8	−0.8	+0.8	214.417	214.809	215.272	1.57	1.64
339.634	−0.8	+0.8	339.313	339.658	339.998	1.50	1.55
244.184	−0.8	+0.8	243.898	244.214	244.554	1.78	1.82
517.4	−0.8	+0.8	516.071	517.325	517.635	1.45	1.52
292	−0.8	+0.8	291.587	292.004	292.587	1.60	1.65
567.9	−0.8	+0.8	567.479	567.901	568.421	1.47	1.53
305.5	−0.8	+0.8	305.109	305.485	305.996	1.92	1.83
712	−0.8	+0.8	711.54	712.978	712.342	1.85	1.62
321.8	−0.8	+0.8	321.524	321.786	322.149	2.22	1.94
833.6	−0.8	+0.8	833.310	833.582	834.926	1.76	1.85
350	−0.8	+0.8	349.678	350.014	350.373	1.75	1.84
990.4	−0.8	+0.8	990.075	990.417	990.758	1.54	1.60
325	−0.8	+0.8	324.760	325.051	325.386	2.00	1.93
1653.3	−0.8	+0.8	1652.910	1653.318	1653.700	1.51	1.50
199	−0.8	+0.8	198.719	199.024	199.358	1.57	1.57

Table 16. Cont.

Nominal Dimension	Lower Tolerance	Upper Tolerance	Minimum Measured Value	Average Value	Maximum Measured Value	C_pK	P_pK
1594.124	−0.8	+0.8	1593.840	1594.092	1594.390	1.96	1.90
214.8	−0.8	+0.8	214.421	215.026	214.802	1.92	2.10
1483.7	−0.8	+0.8	1483.42	1483.695	1484.060	1.72	1.80
244.5	−0.8	+0.8	244.281	244.512	244.893	2.01	2.03
1306.6	−0.8	+0.8	1306.310	1306.621	1307.160	1.56	1.64
292	−0.8	+0.8	291.843	291.981	292.149	3.60	3.47
1112	−0.8	+0.8	1111.79	1112.002	1112.130	3.55	3.79
321	−0.8	+0.8	320.659	321.014	321.308	1.44	1.50
1256.1	−0.8	+0.8	1255.72	1256.079	1256.480	1.51	1.57
305	−0.8	+0.8	304.640	305.025	305.372	1.46	1.58
345	−1	+1	344.606	344.954	345.372	1.76	1.70
345	−1	+1	344.474	345.003	345.314	1.77	1.89
5	−1	+1	4.615	4.992	5.49	1.54	1.62
5	−1	+1	4.696	5.016	5.546	1.80	1.83
12	−1	+1	11.593	12.022	12.465	1.58	1.65
12	−1	+1	11.349	11.995	12.428	1.52	1.53
17.1	−1	+1	16.809	17.106	17.520	2.22	2.13
17.1	−1	+1	16.674	17.136	17.540	1.75	1.62

The results showed that all 50 analyzed parts were within the specified limits, with no deviations exceeding the allowable tolerances.

In addition to the dimensional inspections, a process capability study was conducted on the same sample of parts. The purpose of this study was to evaluate process stability and precision after the implementation of corrective actions. The capability study provided a quantitative statistical analysis of process performance, ensuring that the process is not only controlled but also capable of consistently producing conforming parts. The capability study was conducted using Minitab software v 18 (Figure 22). In the capability study, the capability indices were analyzed according to the standard [3] as follows:

1. C_pK (Process Capability Index)

➤ Minimum acceptable: $Cpk \geq 1.33$

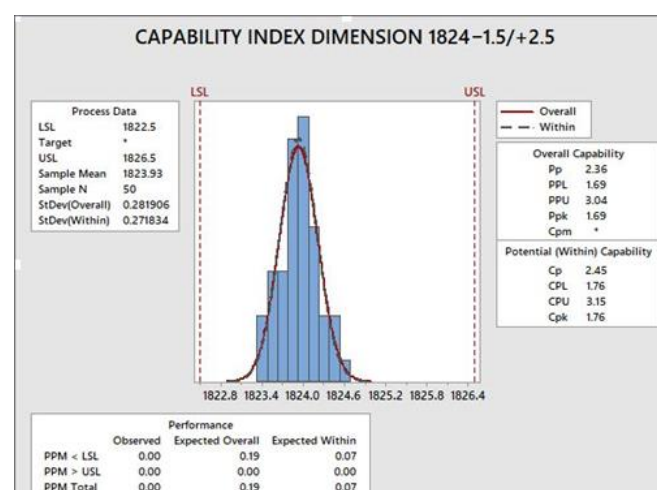


Figure 22. Example of a capability report generated in Minitab. The symbol * represents that Cpm is not evaluated yet. The blue bars represent the frequency distribution of the measured values within the process.

C_pK is calculated as follows:

$$C_pK = \min\left(\frac{USL - \bar{X}}{3\sigma}, \frac{\bar{X} - LSL}{3\sigma}\right) \quad (3)$$

where

- USL = Upper Specification Limit.
- LSL = Lower Specification Limit.
- $\bar{X}$ = Process mean.
- σ = Short-term standard deviation (calculated from grouped data, e.g., samples of 5 parts, multiple sets).

2 P_pK (Process Performance Index)

- Minimum acceptable: $P_pK > 1.50$

P_pK is calculated as follows:

$$P_pK = \min\left(\frac{USL - \bar{X}}{3s}, \frac{\bar{X} - LSL}{3s}\right) \quad (4)$$

where

- s = Overall standard deviation of the process (long-term variation).

This chart is a histogram of the capability index for dimension 1824, used in the analysis of production process quality. The blue bars represent the frequency distribution of the measured values within the process. In other words, they show how often certain values of the measured dimension (around the target value of 1824) occur in the analyzed sample of 50 measurements.

The capability study enabled a quantitative analysis of process performance from a statistical perspective, ensuring that the process is not only controlled but also capable of consistently producing conforming parts.

4.4.5. Verification of Actions Implementation and FMEA

All established actions were implemented and integrated into the FMEA (Table 17), updating severity, occurrence, and detectability to support the continuous improvement of the prevention system and risk control resulting in a medium level, represented by the color yellow, and a low level, also indicated by the color green, for the Action Priority (AP) index. After the implementation of the corrective actions, the AP index level is low for all failure effects.

Table 17. Failure mode and effects analysis of laser cutting. With color yellow are represented medium levels of risk and with color green low levels of risk

Failure Effects (FE)	S	Failure Mode (FM) of Process Step	Failure Cause (FC) of Work Element	Current Prevention Control of FC	O	Current Detection Control of FC & FM	D	AP	Prevention Action	Detection Action	Status	S	O	D	AP
1 Impossibility of mounting on the customer intern: 5 next customer: 5 final customer: 6	6	Positioning deviations of the holes relative to the X and Z axes compared to the nominal values specified in the technical documentation	The inspection tools promote non-conforming parts; the templates for dimensional inspection of parts are incorrectly designed	General rules for laser tube	7	Checking of information on the drawing and OF	7	M	Manufacturing and integration of machined blocks to ensure limitation and repeatability of positioning on the X, Z axis.	Creation of a template for checking hole positioning (attribute-based). Three-dimensional control of one piece per batch. Process monitoring through statistical process control.	100%	6	4	5	L
2 Impossibility of mounting on the customer intern: 5 next customer: 5 final customer: 6	6	Positioning deviations of the holes relative to the X and Z axes compared to the nominal values specified in the technical documentation	The locking elements related to the X and Z axes show deformations in the upper area	General rules for laser tube	7	Frequency self-control rates realized by the operator and quality inspector that is documented on OF; checking of the first part	6	M	Manufacturing and integration of machined blocks to ensure limitation and repeatability of positioning on the X, Z axis.	Calibration and verification of dimensional inspection device.	100%	6	4	5	L
3 Impossibility of mounting on the next step intern: 8 next customer: 8 final customer: 8	8	Position NC of the hole	Bad set up of the glasses by operator	Checking of the glasses with the caliper after each set up of the machine; FI-RO 780 General rules for laser tube (checking of each start up of the set up the glasses)	3	Checking of the first part and Frequency Checking	3	L							
4 Impossibility of mounting on the next step intern: 8 next customer: 8 final customer: 8	8	Position NC of the hole	Gap machine on y	FI-RO-780 Laser tubes general rules the checking of the set up of the machine on y	3	Checking of the first part and Frequency Checking	3	L							
5 Impossibility of mounting on the next step intern: 8 next customer: 8 final customer: 8	8	Position NC of the hole	Defect of straightness of tube	Integration in laser tubes general rules the checking of straightness of tube	3	Checking of the first part and Frequency Checking	3	L							

5. Results

The implementation of our proposed solution was carried out using the following hardware components.

Following the implementation of the corrective measures—the development of a dedicated template for hole positioning verification (through attribute control), the design and integration of machined blocks to ensure limitation and repeatability of positioning on the Z-axis, as well as the rigorous calibration of the dimensional verification fixture—product conformity was successfully restored—Table 18.

Table 18. Components of the solution.

Component	Specifications	No
Video camera (simulation using images)	Surveillance camera Imou (Dahua Technology, Hangzhou, China) 5 MP Resolution 2592×1458	4
Current consumption measurement circuit	Pressac CT Clamp + gateway 60A	2
Server	Intel Core i9, 2,6 GHz, 14 cores, 40 GB RAM, 1 TB SSD	1
Communications	Existent infrastructure (cables, routers, switches)	1

The analysis of the performed inspections and the close monitoring of the process highlighted the elimination of hole positioning deviations relative to the X and Z axes, deviations that had previously been reported against the nominal values defined in the technical documentation. The batches of parts delivered in April fully complied with customer requirements, with no new complaints being recorded.

Performance indicators, both external PPM (Figure 23) and internal PPM (Figure 24), confirmed the stability of the process, with both values remaining below the target thresholds, while the costs associated with non-quality were significantly reduced (Figure 25).

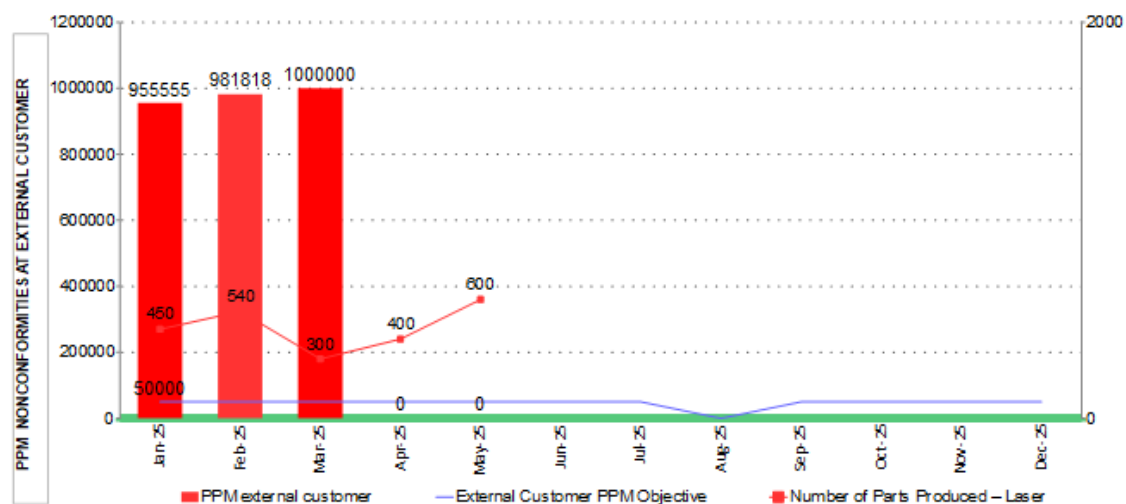


Figure 23. External PPM.

In the initial situation, the production process exhibited a high level of nonconformities, as reflected by the quality indicators. The external PPM value reached levels of up to 1,000,000, while the internal PPM was approximately 55,000, significantly exceeding the limits accepted within the organization. Consequently, non-quality costs amounted to as much as 12,916 EUR, including losses associated with scrap, rework operations, and risks arising from customer complaints.

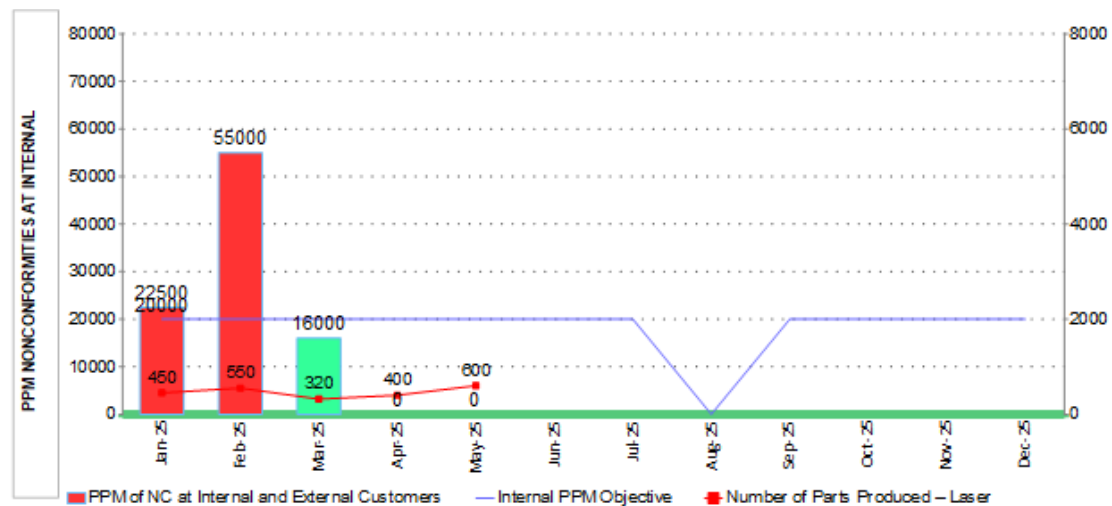


Figure 24. Internal PPM.

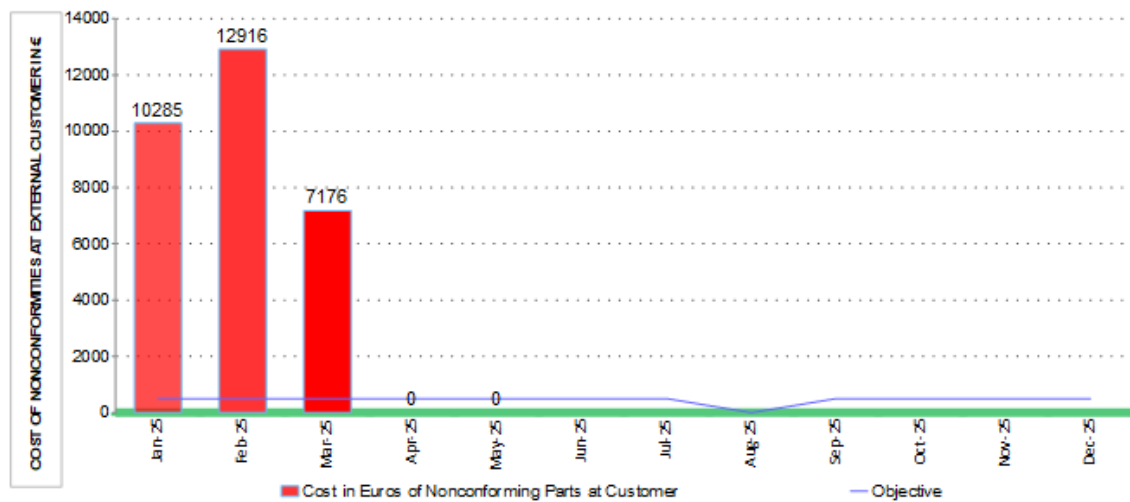


Figure 25. Cost of non-quality.

To address this situation, corrective actions were implemented, targeting both the integration of Industry 4.0 technologies across all stages of the 8D methodology and the direct improvement of the production process. These actions included adjusting and modifying the devices used, optimizing workflows, and ultimately stabilizing the production process.

As a result, the quality indicators improved significantly: both external and internal PPM values were reduced to zero, demonstrating the complete elimination of defects in customer deliveries as well as in internal process control. In parallel, non-quality costs were reduced to zero, confirming the effectiveness of the implemented actions and ensuring the long-term stability of the production process.

Produced/Nonconforming Parts

- March: 400 parts delivered/0 nonconforming parts delivered.
- April: 600 parts delivered/0 nonconforming parts delivered.

Produced/Nonconforming Parts

- March: 400 parts produced/0 nonconforming parts produced.
- April: 600 parts produced/0 nonconforming parts produced.

6. Conclusions

This paper presented an 8D analysis centered on a case study from the automotive industry. It covered the entire 8D analysis flow, from the occurrence of the complaint to the implementation of corrective actions. In addition, it introduced a solution based on modern Industry 4.0 technologies. The solution is implemented with advantages in terms of response time, the resolution of spatial organization issues for components involved in the production flow, the acquisition of equipment-related data, and the collection of data into a single library that can be used to handle future cases very efficiently.

The following points were addressed and achieved in this article: an 8D analysis for a case study in the automotive industry; the implementation of Industry 4.0-specific technologies (such as Artificial Intelligence, the Internet of Things, and a Reports Engine); and the development of a complete framework for 8D analysis. Clearly, the pilot study presented in this article will be developed into a complete solution that could potentially be parameterized for different production processes.

The present study demonstrated the efficiency and relevance of the 8D method in managing and resolving nonconformities occurring in automotive production processes. This study is applied to a concrete case concerning the positioning deviations of holes on a component used in the assembly of refrigeration units for trailers. The identified issue—dimensional deviations along the X and Z axes—affected 300 parts and generated a formal customer complaint, highlighting a negative impact both on the assembly process and on quality indicators.

By applying the 8D methodology, it was possible to isolate the problem, analyze the actual causes, and implement a corrective and preventive action plan. According to the 8D audit conducted on 31 March 2025, the measures taken were validated as effective, and positioning deviations were no longer observed. Among the technical actions implemented were the replacement of the centering groups with machined blocks, which ensured repeatable positioning on the Z axis; the calibration and optimization of the “go/no-go” inspection device; and the creation of a control template with fixed reference points and a dedicated gauge. The data collected following the implementation of these actions indicate significant improvements. The process Cpk value for hole positioning reached a minimum of 1.39, with an average of 1.76, while Ppk reached up to 3.79, exceeding the minimum threshold of 1.33 and demonstrating both process capability and stability. The PPM value for internal and external nonconformities was reduced below the critical thresholds of 20,000 and 50,000, respectively. Non-quality costs, which previously exceeded 500 euros, were reduced to zero thanks to the preventive and control measures. Furthermore, the attribute-type R&R analysis showed an efficiency of over 90%, with less than 2% of defects overlooked and under 5% of the good parts incorrectly identified as defective, validating the reliability of the measurement and decision-making system. In addition, the integration of the FMEA method according to VDA-AIAG [7] enabled a proactive risk assessment and the prioritization of actions based on the AP (Action Priority) indicator, replacing the traditional RPN. This preventive approach was complemented by tools such as SPC, which supported continuous process monitoring through statistical control and facilitated data-driven decision-making.

The results highlight not only the elimination of the problem’s root cause but also the strengthening of a robust quality system. Through the actions undertaken, the organization improved its ability to respond quickly and effectively to nonconformities—and more importantly, to prevent them—by integrating lessons learned and standardized measures into future work plans.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
LLM	Large Language Model
IoT	Internet of Things
RE Analysis	Root Cause Evaluation Analysis
PDCA	Plan-Do-Check-Act
VSM	Value Stream Mapping
FMEA	Failure Mode and Effects Analysis
PPM	Parts Per Million—here regarding fault rate

References

1. Mahmood, K. Solving Manufacturing Problems with 8D Methodology: A Case Study of Leakage Current in a Production. *Company. J. Electr. Electron. Eng.* **2023**, *2*, 1–18.
2. Pauliková, A. Visualization Concept of Automotive Quality Management System Standard. *Standards* **2022**, *2*, 226–245. [CrossRef]
3. IATF 16949 GM Customer Specific Requirements—Effective 1 March 2025. Available online: <https://www.iatfglobaloversight.org/wp/wp-content/uploads/2025/10/IATF-16949-GM-Customer-Specific-Requirements-October-2025.pdf> (accessed on 17 July 2025).
4. Ford Motor Company Customer Specific Requirements for IATF 16949:2016—Effective 23 June 2025. Available online: https://www.iatfglobaloversight.org/wp/wp-content/uploads/2025/06/Ford-IATF-CSR_June-2025-Release-FINAL.pdf (accessed on 17 July 2025).
5. Lestyánszka Škúrková, K.; Fidlerová, H.; Niciejewska, M.; Idzikowski, A. Quality Improvement of the Forging Process Using Pareto Analysis and 8D Methodology in Automotive Manufacturing: A Case Study. *Standards* **2023**, *3*, 84–94. [CrossRef]
6. Phanden, R.K.; Sheokand, A.; Goyal, K.K.; Gahlot, P.; Demir, H.I. 8Ds method of problem solving within automotive industry: Tools used and comparison with DMAIC. *Mater. Today Proc.* **2022**, *65*, 3266–3272. [CrossRef]
7. Enache, I.-C.; Chivu, O.R.; Rugescu, A.-M.; Ionita, E.; Radu, I.V. Reducing the Scrap Rate on a Production Process Using Lean Six Sigma Methodology. *Processes* **2023**, *11*, 1295. [CrossRef]
8. Chen, P.S.; Chen, J.C.M.; Shen, B.M.; Chen, G.Y.H. Implementation of Ford 8D in Improving Efficiencies of Wafer Testers: A Case Study. *Eng. Manag. J.* **2025**, 1–13. [CrossRef]
9. Barosani, S.; Bhalwankar, N.; Deshmukh, V.; Kokane, S.; Kulkarni, P.R. A review on 8D problem solving process. *Int. Res. J. Eng. Technol.* **2017**, *4*, 529–535.
10. Kumar, S.; Verma, M.; Dubey, D. Reducing the defects and improving the quality of manufacturing product (CT wheel/crain part) using 8D problem solving tool. *Indian. J. Sci. Res.* **2023**, *3*, 47–55.
11. Kempel, M.; Richter, R.; Deuse, J.; Schmid, S.; Schulte, L. Knowledge Graph-Based Approach for Interactive Problem Solving with the 8D Method. In Proceedings of the Smart Systems Integration Conference and Exhibition (SSI), Brugge, Belgium, 28–30 March 2023; pp. 1–5.
12. Divanoğlu, S.U.; Taş, Ü. Application of 8D methodology: An approach to reduce failures in automotive industry. *Eng. Fail. Anal.* **2022**, *134*, 106019. [CrossRef]
13. Huszák, C.; Pinke, P.; Kovács, T.A. Tools for a Root Cause Analysis for Safety–Critical Components Areview. In *The Impact of the Energy Dependency on Critical Infrastructure Protection, Proceedings of the ICCECIP 2024, Budapest, Hungary, 7–8 November 2024*; Kovács, T.A., Stadler, R.G., Daruka, N., Eds.; Advanced Sciences and Technologies for Security Applications; Springer: Cham, Switzerland, 2025.
14. Ichimov, M.A.M.; Popescu, M.V.; Negoita, O.D.; Costea-Marcu, I.C.; Moiceanu, G. Proposal for software management solution to prevent potential issues. *U.P.B. Sci. Bull. Ser. C* **2025**, *87*, 107–120.

15. Yao, L.; Huang, H.; Chen, S.H. Product quality detection through manufacturing process based on sequential patterns considering deep semantic learning and process rules. *Processes* **2020**, *8*, 751. [\[CrossRef\]](#)
16. Bozyiğit, F.; Doğan, O.; Kılınc, D. Categorization of customer complaints in food industry using machine learning approaches. *J. Intell. Syst. Theory Appl.* **2022**, *5*, 85–91. [\[CrossRef\]](#)
17. Xie, T.; Yao, X. Smart logistics warehouse moving-object tracking based on YOLOv5 and DeepSORT. *Appl. Sci.* **2023**, *13*, 9895. [\[CrossRef\]](#)
18. Rahmatov, N.; Paul, A.; Saeed, F.; Hong, W.H.; Seo, H.; Kim, J. Machine learning-based automated image processing for quality management in industrial Internet of Things. *Int. J. Distrib. Sens. Netw.* **2019**, *15*, 1550147719883551. [\[CrossRef\]](#)
19. Oliveira, D.; Alvelos, H.; Rosa, M.J. Quality 4.0: Results from a systematic literature review. *TQM J.* **2025**, *37*, 379–456. [\[CrossRef\]](#)
20. Sima, D.; Potra, S.; Pugna, A. Enhancement of Customer Complaints: Digitalization of Synchronous Model for Problem-Solving of Manufacturing Complaints. *Procedia Comput. Sci.* **2024**, *242*, 1015–1023. [\[CrossRef\]](#)
21. Pietsch, D.; Matthes, M.; Wieland, U.; Ihlenfeldt, S.; Munkelt, T. Root cause analysis in industrial manufacturing: A scoping review of current research, challenges and the promises of AI-driven approaches. *J. Manuf. Mater. Process.* **2024**, *8*, 277. [\[CrossRef\]](#)
22. Hermann, M.; Bucker, I.; Otto, B. Industrie 4.0 process transformation: Findings from a case study in automotive logistics. *J. Manuf. Technol. Manag.* **2020**, *31*, 935–953. [\[CrossRef\]](#)
23. Realyvásquez-Vargas, A.; Arredondo-Soto, K.C.; García-Alcaraz, J.L.; Macías, E.J. Improving a Manufacturing Process Using the 8Ds Method. A Case Study in a Manufacturing Company. *Appl. Sci.* **2020**, *10*, 2433. [\[CrossRef\]](#)
24. Rath, R.; Reddy, M.C.G.; Narayana, A.L.; Narayana, U.L.; Rahman, M.S. Investigation and implementation of 8D methodology in a manufacturing system. *Mater. Today Proc.* **2022**, *50*, 743–750. [\[CrossRef\]](#)
25. Oancea, A.-V.; Rontescu, C.; Bogatu, A.-M.; Cicic, D.-T. Using the Ishikawa diagram for problem analysis in the laser cutting process. *J. Res. Innov. Sustain. Soc. (JRISS)* **2024**, *6*, 109–118. [\[CrossRef\]](#)

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