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USING PROCESS FAILURE MODE EFFECT AND ANALYSIS (PFMEA) FOR RISK REDUCTION IN AN ELECTRICAL PANEL COMPANY

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Abstract: Process quality assurance is indispensable for the satisfactory outcome of finished products on a production line. PFMEA is a proactive and preventive tool that may help improve processes. This article aimed to reduce the risks of non-quality and customer dissatisfaction by applying the PFMEA methodology in the process automation sector for production lines of medium and low-voltage equipment that have manufactured processes. As a methodology, a literature review was carried out to understand the scenario of other companies, followed by action research to apply changes in the studied process. The developed solution is presented, and the risk reduction results are discussed. Of the 89 identified risks, 64 (71%) were reduced by applying the solution with integrated automation on the workstation with the highest number of risks (79%).

Key words: process automation, PFMEA, risk control, quality management.

1. INTRODUCTION

Customer satisfaction is one of the main pillars in the market guarantee of a brand, whatever the segment in question, [1]. For the electric power sector, product quality is fundamental and also means the safety of customers and their property, especially when it comes to the medium and low-voltage panels field. Thus, when applied in power distribution and management, equipment needs to be designed and produced with quality criteria and without waste.

In this context, the processes need to be carefully planned and controlled to achieve the quality of the finished product, from understanding the customer's need to all the internal steps and the production of the equipment until it is packaged and awaiting collection by the customer. How, then, may one ensure product integrity proactively, avoiding failures, complaints, and customer dissatisfaction?

The evolution of quality concepts and the development of industry-applicable tools have made it essential to invest in preventing problems rather than correcting them. The Failure Mode Effect and Analysis (FMEA) methodology, the focus of this study, is used to analyze potential process or product failures/risks to act preventively. When applied in manufacturing processes (PFMEA), it is possible to identify the critical points of the process, assess its safety and control, and determine the necessary improvement points, thus ensuring product delivery according to specifications, [2].

Once the risks are appropriately identified, process automation may be a great tool to reduce them, as in the case of manufactured processes with high variability, in which production is not en masse, so automation must be applied strategically, acting on points that can be standardized, working side by side with manufacturing. In a critical segment such as this, one cannot wait for failures to occur, and risks mapped as critical in the FMEA must be reliably reduced and controlled, which may be achieved through automation.

In addition, Lean Manufacturing, developed in Japan as a technique to maximize product value through waste reduction, defines everything that does not add visible value to the customer or consumer as waste and maps defects as one of eight main types of waste, [3]. Even though testing and inspections may prevent the customer from facing problems in the field, they are corrective methods that allow the defect to occur. Generating defects produces non-quality costs and rework and adds time to the process, which may be avoided by working preventively and proactively.

Thus, combining automation with quality methodologies and applying them strategically to complement the manufactured processes, thus reducing non-quality risks, is one of the approaches that may be taken. Given this context, this study aimed to reduce the risks of non-quality and customer dissatisfaction by applying the PFMEA methodology in the process automation sector for production lines of medium and low-voltage equipment that have manufactured processes. For such, a theoretical review identified how the PFMEA methodology has been applied in the industry, and the Risk Priority Number (RPN) concept and its importance were understood. Later, the action research detailed the operation of the production line located in Blumenau/Brazil, evaluated the current state of the process using the PFMEA methodology, identified the high RPNs, and verified whether the solutions were able to reduce the mapped risks.

2. METHODOLOGY

The methodology used was divided into two parts: the theoretical step and the practical step. The theoretical step consisted of a systematic literature review using the Science Direct, Scopus, and IEEE databases, combining the words that referred to the objective of the study of relating the PFMEA methodology with the application of automation in manufactured Engineering to Order (ETO) production lines. The questions to be answered were the following: a) what is PFMEA and how is it applied?; b) what is RPN and how to reduce defects from its use?; c) how may automation help in PFMEA?; d) what is the relationship between Industry 4.0 and automation?. Nineteen articles were analyzed to answer the questions listed.

For the practical step, action research was carried out in which the authors participated in developing the studied project, both in the PFMEA reviews and in validating the proposed solutions. Thus, we began with the description of the company, product, and production line, followed by the process flow chart. Next, the failure modes related to each step of the process were diagnosed, the failure classification criteria, such as levels of severity, occurrence, and detection, were defined, and the failures were quantified. Finally, the risks and respective proposed solutions were identified, and the improvements obtained were compared.

3. LITERATURE REVIEW

This section describes the theoretical concepts of PFMEA that are important to assist in identifying the failure modes of the production line studied in the action research and their relationship with ETO and lean manufacturing error-proof devices (poka-yoke).

Approximately since the 1990s, quality has changed from a corrective approach to a holistic approach focused on defect prevention, and the importance of the methods and tools used in the automotive industry for quality management is indisputable, [4]. Defect elimination may be understood as the basis of the lean methodology production strategy, [5], and the classic FMEA approach is used to deliver high-quality products and optimize production systems, [6]. Among the benefits of the tool, one may mention the prevention of failures, identification of critical aspects of the process, design and control areas, continuous improvement, and cost optimization, [7].

As [8] described, FMEA is a systematic methodology for identifying and predicting problems before they occur. It emerged in the military area in the United States in the late 1940s, was applied to the aerospace industry in the 1960s, and came to industry through Ford in the late 1970s, being a tool to measure the reliability of products and processes. In turn, focused on the process, PFMEA consists of three factors: Severity, Occurrence, and Detection. Severity is a number associated with the impact and criticality of the evaluated failure mode, considering the customer's point of view regarding their product. Occurrence is associated with the cause of the failure mode, thus being the form of control of this cause, resulting in the probability of failure occurrence. In turn, detection is given according to the chance of non-detection of the failure throughout the production process, [9]. The three elements are evaluated and assigned values independently, i.e., the severity value is independent of the detection and occurrence values, with the reverse also being true for both factors.

RPN allows failure modes to be classified by their criticality, indicating which process steps are most likely to fail and affect the customer. Based on the evaluation of the RPN, actions should be defined to strengthen the process, either by improving the controls of the causes of failure, thus reducing the occurrence, or by enhancing the way of detecting failures, decreasing the chance of non-detection, [9]. The main objective of using PFMEA is to reduce failures based on their priority, [7].

[10] described how using PFMEA applied to the analysis of failures that influence the Overall Equipment Effectiveness (OEE) of a sugar production process machine, together with the Fuzzy methodology for prioritizing risks, increased the OEE by 6%. Other examples of application of the PFMEA methodology are common outside the automotive and aerospace industries, such as the case presented by, [7], who applied the

tool to reduce the incidence of failures due to communication between humans and machines in a collaborative work spot welding cell. The results found in the main studies analyzed are shown in Table 1.

Table 1. PFMEA application examples

Reference	Location	Results presented
[1]	Application of automation for defect reduction	Theoretical review on the use of automation for zero defects. Results from 145 articles were presented, listing different segments and methodologies applied in search of zero manufacturing defects.
[2]	Automation of FMEA and 8D methodology	Explanation related to the use of PFMEA and proposition of an automated system to integrate quality tools and accelerate customer response.
[7]	Automated welding process	Application of PFMEA in an automation scenario. The authors identified ten failures in the automated process and three in the manual process and, based on the risks, proposed actions to reduce the failures.
[11]	Risk assessment in the context of highly automated vehicles	Application of FMEA to the highly automated vehicle scenario. The authors concluded that the FMEA methodology is a valid method for identifying and evaluating safety and reliability at the level of driving automation.
[9]	Application of FMEA in general	The authors addressed the relevance of reducing manufacturing errors in industries and the methodology detailed in six steps of how to conduct an FMEA.
[5]	Collaborative assembly cell between humans and robots	Poka-yoke proposals to reduce the incidence of failures in a collaborative assembly cell between humans and robots.
[10]	Application of PFMEA to increase machine efficiency	Applying PFMEA in conjunction with the Fuzzy methodology resulted in a 6.05% increase in OEE with the actions being taken.

For the studied scenario, it is important to highlight the concept of an ETO production. According to, [12], ETO companies are commonly engaged in manufacturing complex products with relevant engineering components of high added value, and their chief characteristics are high customization, high complexity (high value added to products), project-based, customer-centric, and low volume or "one-of-a-kind". This structure is illustrated in Figure 1.

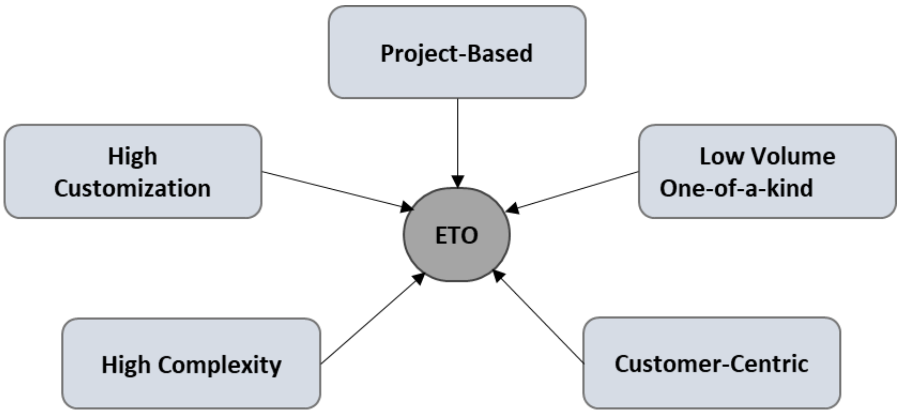

Fig.1. Chief ETO characteristics (Adapted from 12)

Turning to the context of Industry 4.0, which enters the scene when it comes to process automation for error reduction, during a survey conducted with 30 experts from the German ETO industry, [13] observed that the companies interviewed still did not understand the requirements that were born with Industry 4.0. The authors also mentioned that the few Industry 4.0 requirements met came from customer requests, reinforcing the market trend in this direction. A review of progress and emerging issues of the last decade (2010–2020) focused on the supply chain for ETO companies carried out by, [14] pointed out Industry 4.0 and other topics driven by technological developments as emerging in this period and as challenges to be studied for the next decade. In the current scenario, in which manufacturing quality assurance is a critical factor for industries, automation, rapid technological transformations, and Industry 4.0 are able to bring companies closer to zero manufacturing defects scenarios, [1].

4. ACTION RESEARCH IN THE COMPANY OF LOW AND MEDIUM-VOLTAGE PANELS

This section describes the context of the studied company, the production line used as the object of study, the analyses carried out using the PFMEA methodology, the main risks identified, and finally, the proposed solution to reduce them. For confidentiality reasons, some information has been adapted to preserve the identity of the company.

The action research was carried out in a company that manufactures low and medium-voltage equipment at its Santa Catarina plant, with it being an ETO company that works with customized projects according to customer needs. Among the six main products offered by the company, five fit into the ETO category and one into the Configured-to-Order (CTO) category, which may be understood as an offer with approximately 20% freedom of customization at the customer's request. Of these products, one consists of a low-voltage panel, four are medium-voltage panels, two of which are intended for primary distribution networks and the other two for secondary distribution networks, and one is a product line. The company has been in operation since 1976 and belongs to a multinational company specializing in energy management with plants in more than 100 countries; in Blumenau, it has approximately 230 direct employees and 120 outsourced workers. The first step was the Process Flow Diagram (PFD) considering the production flow of this new offer, which was the basis for constructing the PFMEA analysis, shown in Figure 2.

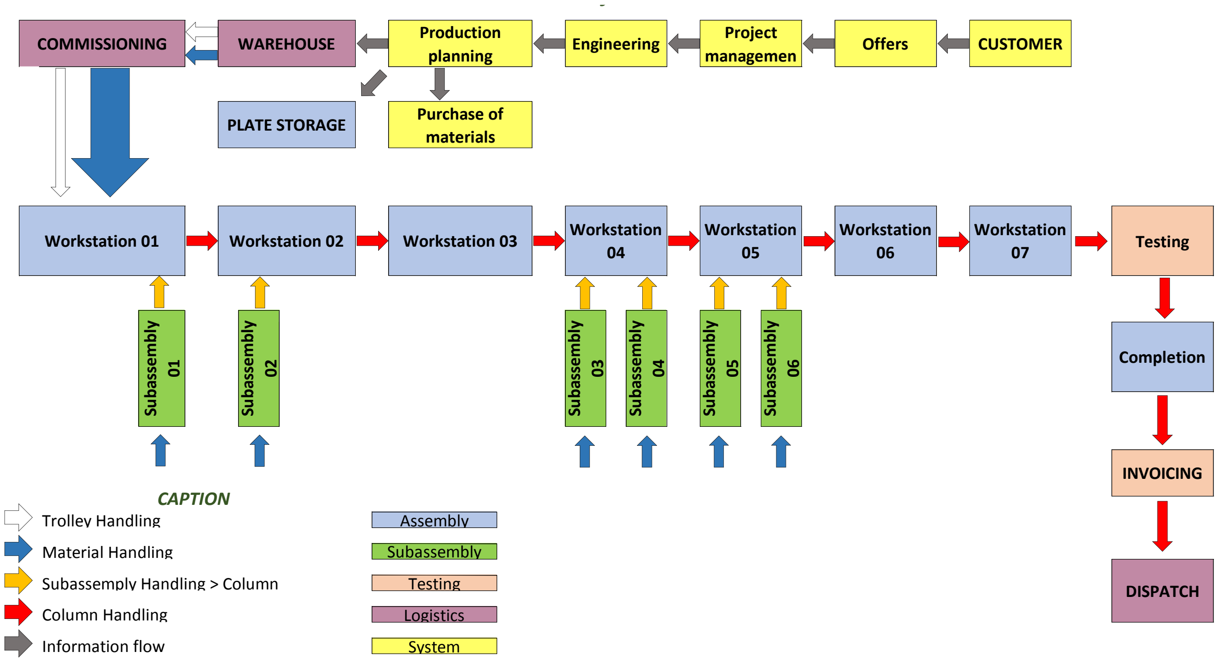

Fig. 2. Process Flow Chart

The construction of the product process flow occurred from the order by the customer, contemplating the flow of materials, passing through the testing steps, and ending with the product "ready" for delivery or pick-up by the customer, again a logistics step. During the PFD, it was identified that the complete assembly would be carried out over eight assembly stations and six substations, one standard test step, and a Factory Acceptance Test (FAT) step, which are the tests performed with the finished equipment that the customer may follow. The main difference between the product in question and the products already manufactured at the Blumenau plant was the technology used, given that the equipment had an air-insulated medium-voltage switch, unlike the other switches used in other lines.

To evaluate the failure modes, a multidisciplinary team was formed with representatives from the production

area: one technician responsible for the product, one responsible for testing, one responsible for methods and processes, one responsible for the quality sector, one responsible for the maintenance, and one responsible for the project management. It required a team capable of understanding and discussing the various steps, who had prior knowledge relative to historical data, and who were concerned with the quality of deliveries.
Together with the team, 318 failure modes were raised to be analyzed, with only eight related to the information flow and 310 to the production line or logistics movements. The risks identified relative to the information flow and logistics were, in general, applicable to other offers of the plant, so there were already control modes and preventive measures in place that could be applied to the product being analyzed. The study in question focused on the failure modes and analyses carried out relative to the production line. While the values in the standard methodology may vary from one to ten, in the studied company, five levels are determined to rank Severity and only four levels to rank Occurrence and Detection. Table 2 shows the criteria considered for severity.

Table 2. Criteria used for severity

Severity	Level	Effect of failure on the end-user (or internal) customer	Affected characteristics
1	Imperceptible	**Undetectable by the customer.** Potential Failure Effect: No noticeable effect on product functionality. *The customer is unlikely to be aware of this*	Esthetic convenience (except when required for a specific product)
4	Performance	**Remains operational**. Potential Failure Effect: Some degradation of the product at the subsystem level, but the performance of the main systems is not affected. *The customer is uncomfortable or irritated.*	Degradation of a secondary function and/or subsystem
7	Operation	**On-site support is required.** Potential Failure Effect: inoperable subsystems or degradation of the main systems, and the primary functionality of the product is less than customer expectations. *Customer dissatisfaction is experienced.*	Degradation of the main function or critical to quality
9	Material damage	**Significant impact on customer business, destruction of part of the facility, impossible initialization.** Potential Failure Effect: non-compliance with the regulation (lawsuit risk or huge cost) or an inoperable product at the highest levels of the system but not related to safety. *The customer is highly dissatisfied*	Integrity of the property and/or stoppage of deliveries
10	Safety – Human risk	**Only a potential safety issue.** Potential Failure Effect: unacceptable risk of injury or harm to human health. This includes items non-compliant with the regulation that pose a potential direct safety issue. *The customer is in danger.*	Human integrity

As shown in Table 2, with these five levels, it is possible to categorize all the failure effects, which may be of Severity 1, undetectable by the customer, usually involving an esthetic issue, Severity 4, when the equipment remains operational but may have its subsystems or secondary functions degraded, Severity 7, in which case on-site support is required, with the equipment having its main functions degraded, or more critical cases, such as Severity 9, when the customer's property may suffer damages, or Severity 10, which puts people's lives at risk. It is worth noting that the company puts the safety of its employees and customers first, so all cases classified as Severity 10 are reasons for warning. Table 3 describes the possible levels for the occurrence.

Table 3. Criteria used for occurrence

Occurrence	Level	Effect of failure on the end-user (or internal) customer
1	Almost uncertain	**Almost uncertain occurrence.** Presence of a poka-yoke or controlled process with Cpk > 1.66 (short-term capability) and then with Ppk > 1.66 (long-term capability). *Event rarely occurs.*

4	Low	**Low occurrence.** Manual assembly with a jig, with operator assistance, controlled automatic or semi-automatic assembly with $1.33 < Cpk \leq 1.66$ (short-term capability), then with $1.33 < Ppk \leq 1.66$ (long-term capability). *Event sometimes occurs.*
7	Average	**Average occurrence.** Manual assembly without a jig, manual assembly without operator assistance, or automatic or semi-automatic assembly, not capable with $1 < Cpk \leq 1.33$ (short-term capability) or $1 < Ppk \leq 1.33$ (long-term capability). *Event occurs many times.*
10	Almost certain	**Almost certain occurrence.** Uncontrolled and unstable process or when the capability is unknown. *The event almost always occurs.*

Source: Company material

As illustrated in Table 3, the criteria for the occurrence are well-defined and process-oriented. The occurrence may only be set to 1 in the presence of poka-yokes or controlled capability, and it must be ranked as 4 in cases of manual assembly with devices that facilitate the operation. The average occurrence equal to 7 must be considered when there are no devices to aid the assembly, and a high occurrence equal to 10 in cases of uncontrolled processes. Finally, Table 4 presents the possible levels for detection.

Table 4. Criteria used for detection

Detection	Level	Effect of failure on the end-user (or internal) customer
1	Almost certain	**Almost certain detection.** – 100% automatic, semi-automatic with $CamC \geq 4$ and gage $R\&R \geq 90\%$ OR – Jidoka. *The customer will hardly face it.*
4	Average	**Average chance of detection.** – 100% automatic or semi-automatic with $4 > Camc \geq 3$ and gage $90\% > R\&R \geq 80\%$ – 100% manual check with measure, jig, or gauge OR, – 100% human visual inspection, only if low quantity (<100/shift) with: 1– Unambiguous control specification, gage $R\&R \geq 80\%$. 2– The inspector is engaged in control (without self-control). 3– Formal validation of the trained inspector's training with recording. 4– The ability of the inspector is verified on a regular basis with recording. 5– Control result is recorded: checklist with validation, sentinel, touchscreen, Manufacturing Execution System (MES) or – Sample inspection with these two points: 1– with measure, template, or gauge. 2– Statistical Control of the Process in the product/part parameter. *The customer will sometimes face it.*
7	Low	**Low chance of detection.** Human visual inspection with 80 gauges > R&R attributes ≥ 70% OR, Self-inspection or; 100% Automatic or semi-automatic with $Camc < 3$ *The customer will face it many times.*

10	Almost uncertain	**Almost uncertain detection.** Human visual inspection without measurement of gage R&R < 70% OR, – Ineffective control OR, – No control or; – The defect is not controllable or not apparent. *The customer will certainly face it.*

Source: Company material

As represented in Table 4, the criteria for detection are also process-oriented and well-defined to be met. For detection to be 1, it must be automatic or semi-automatic with gage R&R or jidoka (guaranteed detection with a stop at error identification). Average detection with a value of 4 must be manual inspection with measurement or jig, and if there is visual inspection, it must meet the following criteria: 1) unambiguous, controlled by gage R&R (repeatability and reproducibility analysis method that evaluates the reliability of inspections); 2) dedicated inspection; 3) dedicated training and formal validation; 4) periodically verified inspection skills; 5) recorded results. For low chances of detection, there is human self-inspection as Detection 7 and without control as Detection 10. All analyses performed were based on the criteria described in Tables 2, 3, and 4.

5. FINDINGS

During the analysis of the failure modes, we identified that 89 of the 310 related to the production line or logistics resulted in RPNs greater than or equal to 144, which is considered critical. In Figure 3, one may observe the distribution of the identified high-risk lines grouped by Severity.

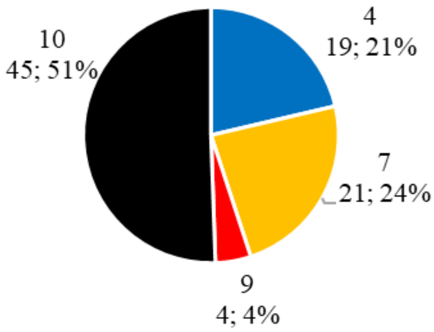

Fig. 3. Severity values identified in failure modes of RPN ≥ 144

Of the 89 high-RPN lines, 70 (78.6%) were from the same workstation, which is responsible for the preparation and assembly of the air-insulated switch, the technology that is the differential of the product. Considering only lines with Severity 10, 41 of the 45 mapped (91%) referred to this station. These data are compiled in Table 5, which shows the number of high risks per workstation among the stations where they were identified.

Table 5. Analysis of workstations by the identified RPN

Workstation	**RPNs ≥ 144**		**RPNs ≥ 144 & Sev. 10**		**RPNs ≥ 144 & Sev. 9**	
Workstation 01	70	79%	41	91%	3	75%
Workstation 02	1	1%	0	0%	0	0%
Workstation 03	1	1%	1	2%	0	0%
Workstation 05	4	4%	0	0%	0	0%
Workstation 06	5	6%	2	4%	1	25%
Subassembly 06	4	4%	0	0%	0	0%
Completion	4	4%	1	2%	0	0%
Total	89	100%	45	100%	4	100%

Table 5 shows that the second station with the highest number of identified high RPNs corresponded to only 6% of the total, a minor value compared to almost 80% of Workstation 01. This may be explained by two factors. The first concerns the technology differentiated from the other types of products. While some failure modes were already addressed in other production lines and the controls were also applicable to the new line, the new insulator used was a new component, so there were still no devices adapted to control the assemblies related to it. The second factor relates to the criticality of the switch for the operation of the product, with it being essential for the equipment to operate. Any failure related to the insulation may compromise the operation of the entire equipment, endangering the customer's property and even their life.

Due to the criticality of the station and considering that the mapping corresponded to almost 80% of the identified high RPNs, this station would be the main point of work for risk reduction. In addition, among many functions performed in the ETO products, the air-insulated switch has an essential function for the product and is standardized in most models, having some variations in positioning and dimension but generally maintaining the same procedures and steps.

Several failure modes were identified throughout the preparation of the switch and its assembly on the panel structure. Although identified in different steps of the process, the failure modes showed similarities despite involving different steps or being related to different components. Therefore, to verify the repeatability of possible problems, the failure modes were grouped into generic categories that specified the type of failure mode. The result of the categorization is presented in Figure 4.

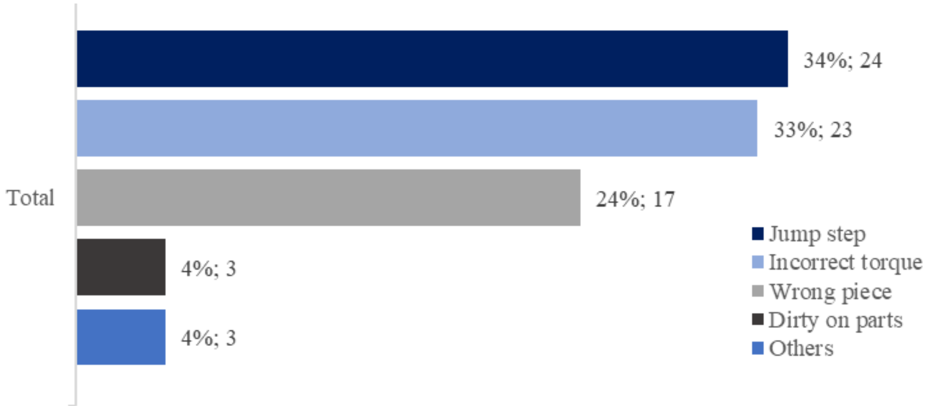

Fig. 4. Categories of identified failure modes

Thus, the main mode of failure identified was the "Skip step", which occurred when the operator "forgot" about a specific component, given the operator was human. In this case, the components listed in the PFMEA were evaluated as critical to the operation of the product. The second most identified failure mode was "Incorrect torque", i.e., the tightness of the connections. As the switch is a primary part of the operation of the column, all its connections must be made according to the specification. Also, because its exterior is made of epoxy, applying torques above the indicated may break or damage the equipment, which is also critical to the product. Choosing the wrong part may also impact the product critically, which is why it appeared as the third category most found among those with high risk. The last two categories, which appeared the same number of times, were "Dirt on parts", specifically for some preparations related to product sealing, and "Others", which include specific failures analyzed that could not be grouped into a generic category. Table 6 summarizes a solution implemented for each failure mode identified in Workstation 01.

Table 6. Risk reduction at Workstation 01

Failure mode	Implemented solution	Number of high RPNs	Reduced number	Relative reduced number
Skip step	HMI synchronized with assembly steps – *Jidoka*	24	24	100%
Incorrect torque	Poka-yoke of the integrated torque system	23	23	100%
Wrong part	Kanban system with indicator lights	17	17	100%
Dirt on parts	Assembly device with adapted jig with ventilation	3	0	0%
Others	-	3	0	0%
Total	-	70	64	91%

Given the identified failure modes and considering the repeatability, particularly of the first three categories raised, a solution of a machine with an integrated human-machine interface (HMI) was proposed, responsible for following the necessary assembly steps at the station in sync with the operator to solve the problem of skipping steps. Adaptive automatic torque control tools that adjust to the torque required throughout the assembly were integrated into this machine to solve the problem of incorrect torques, and, finally, a Kanban system with luminous identifications that indicate to the operator the materials that must be used.
For the failure mode raised related to forgetting components, the proposed solution was to integrate the operations performed by the operator with a digital system that contains the roadmap of assemblies that must be performed. Work instructions were already highly used in the company, but by displaying through an HMI the assembly step currently being carried out in a specific way, the operator may better visualize all the assembly steps. In addition, the system requires a "confirmation" before moving on to the next step, with there being a digital interlock if the operator does not confirm that they performed the operation. The digital interlock works like a jidoka since the system does not allow proceeding to the next step if an operation is not completed. Figure 5 illustrates the mentioned HMI.

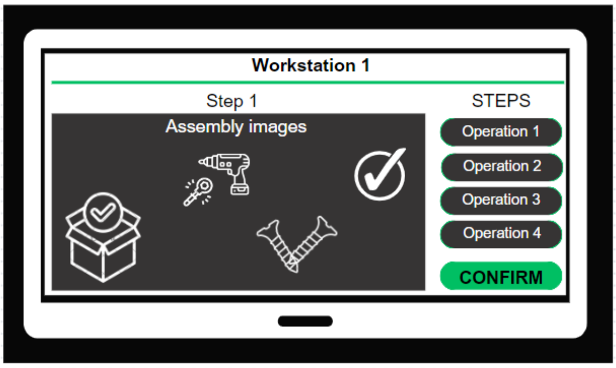

Fig. 5. HMI example

Considering that torques are critical operations, it is indispensable to integrate the operations with the tools used. In this case, through the controller, the tools use the torque programmed according to the roadmap, and the tool itself can detect whether the torque was applied or not and the number of torques that were applied, also comparing this with the number predicted in the roadmap and stopping the operation if the number or application do not agree. As the system is integrated, the controller indicates to the operator which tool and adapter should be used, once again reducing the chance of errors since it will not be possible to fit the tool and perform the operation if the screw used is incorrect, causing the interlocking of the machine. Interlocks are only released with the authorization of the maintenance team.
Torque control is also integrated into the solution, with tools connected to the machine. For the application of torque, the HMI displays to the operator which tool must be used, and the controller sets the appropriate torque according to the operations roadmap; the system only releases the correct tool for activation and only allows the release of the HMI for the next operation after detecting that the torque was applied correctly. Figure 6 shows the controller responsible for setting the torque values according to the operations.
According to the assembly step, the system also indicates the adapter (tip) to be used in the tachometer. Figure 7 shows the workbench with the different adapter options available. The HMI indicates the number to be used, and the indicator light on the workbench also lights up. To ensure that the assemblies were carried out with the appropriate screws, the product is designed with screws of different specifications (either the head fitting or the nominal diameter), and, in addition to ensuring the correct application of torque, the system guarantees that the tachometer will be fitted with the correct screws. For this case, considering the PFMEA criteria, this system works as a poka-yoke (error-proof device), given that it does not allow the operator to use an incorrect tool, i.e., it avoids errors. Moreover, the machine checks whether the torque was successfully applied and blocks the following operations if there is any problem, which allows the Occurrence and Detection to be reduced to level 1.
Finally, given the recurrence of critical materials that may be confused, a system with light indicators for the Kanban system was proposed. In the company, materials were already stocked in Kanban boxes to optimize their supply to the operating line, organization, and ease of access. The integration into the system with light indicators allows the operator to be directed to the correct location to collect the proper material for an operation. The indicators are connected to the system and set according to the HMI roadmap, lighting up when the operator must carry out the assembly of the material. Figure 8 shows an image of the structure used for the

Kanban system, with a luminous identifier positioned in front of the corresponding box.
This solution makes the identification of the material independent of the operator, as it is carried out automatically by the system. Within the PFMEA criteria mapped by the company, this operation may be considered a poka-yoke, thus reducing the Occurrence to level 1 and decreasing the associated risk. Another action identified during discussions with the supplier was related to the failure mode of "dirt on materials", which concerned specific sealing parts that required the application of grease. In this context, an action taken to improve the process was creating a space dedicated to preparing such components and adding an air conditioner to this area.

Fig. 6. System controller


Fig.7. Workbench with adapters

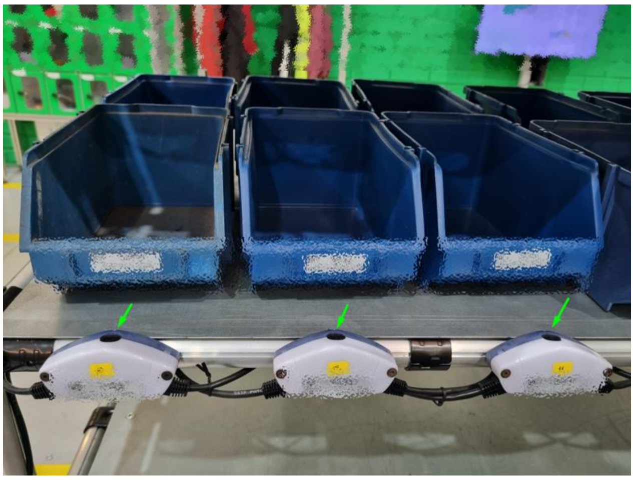
Fig.8. Kanban system with indicator lights

The workbench space may be considered a template, in which specific fittings of the assembly may help the operator carry it out properly. With the use of automation through connected devices, HMI, and light indicators, the solution allowed the improvement of the processes. Hence, the operator works in sync with the system and has fewer chances of error in the operations they must perform. In scenarios in which manufactured processes are still the majority and products are not entirely standardized, a collaborative solution between humans and machines is able to reduce the chance of errors while allowing adaptability with different parts, as in the case in question, in which the machine roadmap may be adapted to the particularities of the different models.

6. CONCLUSIONS

The main objective of this study was to relate the application of PFMEA to a line of manufactured products and reduce the identified risks using automation. Starting with the concept of PFMEA, which is characterized as a methodology for identifying possible failure modes (errors or defects) that may result in customer dissatisfaction, the methodology may be applied to manufactured processes and allows the evaluation of their reliability. In the study in question, the methodology was applied in a production line of medium-voltage panels,

identifying the failure modes present in the process.
Subsequently, to answer what an RPN is and how to reduce its effects, with the practical work we determined that the RPN is the result of the PFMEA analysis, the combination of the assessment of Severity (how severe the impact of the failure is for the customer), Occurrence (what controls exist that prevent the failure mode from materializing), and Detection (if the error occurs, what the sureness that it will be identified internally is). The RPN indicates the points of most significant risk in the process, indicating where controls should be improved, and it may be used for prioritizing actions. If a process is not controlled, there is a higher chance of errors and customer dissatisfaction, and the RPN directs actions to the weak points.
Integrating automation with PFMEA is strategic for reducing the incidence of errors since it can eliminate the "human error" factor, especially in critical processes that may impact the customer. Also, automation improves the reliability of processes. In the evaluated company, under the ETO reality, the lean approach was also used, reinforcing the quality pillar and uniting the flexibility of human work with the "zero defects" guaranteed by machines.
Considering the failure modes, 91% of the risks identified in Workstation 01 were reduced. Of the 89 high RPNs identified in the PFMEA assessment, the reduction of 64 corresponds to 71.9% of the total high risks. Also, in Workstation 01, of the 44 RPNs mapped, 40 were reduced, resulting in 89.8% of total reduction for high severity levels.
For the main mapped problems, such as forgetting process steps, incorrect or not performed torques, choosing the wrong part, and dirt on parts, some of the improvements were focused on developing a machine with a human-machine interface to guide assembly sequencing. Error-proof devices (poka-yokes) and an electronic Kanban system were also implemented, as well as ventilation systems to reduce dirt on parts.
The use of lean manufacturing concepts helped reduce waste, which, added to the automation, reinforced the use of technology in poka-yoke devices and the performance in the quality pillar (jidoka). Evolving to Industry 4.0, it is worth noting that its basis consists of merging technologies with human factors, and automation may be used as a bridge to this. The proposed solution was a machine with an HMI to monitor the assembly process with interlocking that indicates the assembly steps to the human operator, interconnecting tools for torque control and light indications, thus reducing the chance of errors in the operation because it adds the factor "machine/zero defects" in operations involving decision-making, rendering the process more reliable.
This research showed automation systemically, integrating design, management, quality, and relationship with a multidisciplinary team in solving a problem. These criteria complete the profile of an engineer connected to market needs by solving real problems and using technical knowledge as a means of bringing advantages to the company, the customer, and the process. The presented solutions may serve as examples not only for the electric transformer companies but also for other sectors of the economy.
The research problem that motivated this work was the reduction of RPNs with high severity levels identified in the production line in question, and the proposed solution was able to reduce 90% of the mapped risks of Severity 9 and 10, thus not reaching the total goal. Correctly identifying failure modes allows for proposing solutions that include different process steps, as in the studied case.
The particularity of the study performed stands out, given that the literature does not have great coverage for scenarios like this, in which quality methodologies are used to direct automation efforts. As recommendations for future work, reduction alternatives for the unresolved problems may be studied. In such cases, other automation tools (e.g., coupling a cleaning booth to the assembly steps) or even product design changes may be evaluated.

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