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APPLICATION OF THE PROCESSES FAILURES MODELS EFECTS ANALYSIS TECHNIQUE (PFMEA) TO THE NAVAL PIPE MANUFACTURING PROCESS

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Abstract. *This paper proposes the application of the processes failures modes effects analysis technique (PFMEA) to a shipyard located in the state of Pernambuco. The implementation of the PFMEA intends to identify the main failures in the pipe manufacturing process, to indicate the stage of the process that accumulates the highest failure rate, and to measure the impacts they caused to the productivity. This technique also allows us to visualize, in a more objective way, the failures that recurrently occur in the process. Therefore, it is possible to prioritize the most important failures and apply the PFMEA to those ones that are more critical, concentrating the study on the items of greatest impact, from the failures severity point of view to the productive process. Based on the analysis of the results obtained, it was concluded that the PFMEA technique implementation to the construction process of naval pipeline production had a great influence in its continuous improvement, once the use of the tool facilitated the understanding of the behavior of each potential mode of failure and gave direction to the managerial and operational efforts, aiming to minimize or eliminate the risk index.*

Keywords: *FMEA, PFMEA, Process FMEA, Pipe Manufacturing, Naval Pipe.*

1. INTRODUCTION

Attempting to eliminate reworks, the companies often use a strategy in common: the use of tools that identify and measure the failures in a process by degree of importance to then indicate where and what action should be taken to avoid failures and consequently the rework. A tool widely used to identify the failures of a process and its respective impacts caused to the process is the Process Failure Modes and Effects Analysis (PFMEA) technique. Through it, critical points and effective ways of acting against the problem are identified, which can be a simple change of steps in the process, training of those people involved or even the creation of a new system.

It is of utmost importance that instead of being forgotten, failures be mapped and documented so they work as data source and basis for a correct decision making to act in a preventive way to avoid or mitigate the impact generated by the failures in the process (Mcdermott, *et al*., 2009).

This study seeks the application of PFMEA in the process of manufacturing naval piping in a shipyard in the state of Pernambuco. The application of the technique will be very important to give customers the desired quality and guarantee failures occurrence reduction in the process to the yard, reducing reworks and making the yard more competitive in the market. All this converges to a single target, a greater financial return for the company.

2. EXPERIMENTAL PROCEDURE

2.1 Pipes

According to Telles (2001, p.1) can be called pipe a set of tubes and its various accessories.

> In the American nomenclature, the tubes are called "pipe" or "tube". Between the two terms, there is no very rigid distinction. In general, the term "pipe" is used for tubes whose function is to conduct fluids, while the term "tube" is used for pipes destined primarily for other functions, such as exchanging heat (tubular bundles and boiler coils, furnaces, heat exchangers etc.), transmit pressure, conduct signals (instrumentation tubes), function as beams or as structural elements and etc. (Telles, 2001, p.2).

Pipes are very important and very expensive items for industrial or naval assemblies' due to the need to transport fluids from one place to another in operating systems.

2.2 Manufacture of pipes

The prefabrication pipe process for Spool's is realized in a pipe manufacturing workshop, known at construction sites or in the shipbuilding industry as (Pipe-Shop).

According to DAMACENO (2001), the definition of spool consists of a unique piece, which is prefabricated in the pipe manufacturing workshop (Pipe-Shop). The same may consist of one or more sections of pipes or accessories welded together and with the ends prepared for interconnection in the field.

The pipe-shop receives the pipes and connections (curves, tees, crosses, reductions, flanges, nozzles and etc.) and through the so-called prefabricated pipe drawings (also known as sketches) is prepared the cutting plane for better utilization of the tubes and then starts the spool's manufacturing process.

This process consists of:

- Receiving and handling of pipes and connections;
- Chemical pickling, to remove oxidation and impurities;
- Cut and adjust the pipes according to the amount required in the sketch;
- Beveling of pipes and connections;
- Pre-assembly;
- Welding of the joints, indicated in the *sketch* as pipe-shop joints;
- Non-destructive testing (NDT);
- To tag (punctured or welded);
- Forwarding of the spool to the surface treatment process, plating, paint or any other coating type specified by engineering and, finally, are stored for future mounting on the ship.

"The pipe pre-assembly consists in the pre-assembly of a subset composed of a number of pieces of straight pipe and connections". (Telles 2001, p. 204).

2.3 FMEA (Analysis of the failure modes effect)

The first registrations of formal applications of the technique FMEA date of the Decade of 60 in the aerospace industry, then in the chemical process industry where it has become an essential tool for improving the safety and, more recently in the automotive industry for increased quality (Mcdermott, *et al*., 2009).

The technique of Analysis of the Failure Modes Effect (FMEA) is summarized in a group of actions that must be executed systematically in order to know and evaluate the potential failures of a product/process and their respective effects, identify actions to be taken to eliminate or reduce the probability that the failure mode will occur, as well as documenting the analysis process. Each failure mode has a potential effect, some of them are more likely to happen than others. In addition, for each potential effect there is a relative risk associated with it (Mcdermott, *et al*., 2009).

The assessment of the relative risks of failures and its effects is determined by three factors (assessed using a scale from 1 to 10 in ascending order, being respectively low and high, using the data acquired over time and a good knowledge of the process or product):

1. Severity - Consequence in case of failure;
2. Occurrence - Probability or frequency of occurrence of the failure;
3. Detection - Probability of failure detection before the occurrence.

By multiplying the factors (Severity, Occurrence and Detection), it is possible to determine an RPN – Risk Priority Number for each potential failure mode and effect.

RPN = Severity Index **X** Occurrence Index **X** Detection Index (1)

The RPN ranking between 1 and 1000 for each failure mode are used to classify the need for corrective action to eliminate or reduce potential failure modes. Failure modes with the highest RPN should be prioritized, but special attention should be given when the severity ranking is high (9 or 10) independently of RPN.

2.4 FMEA process (PFMEA)

The PFMEA, FMEA of process, operates in failures that may arise in the planning process. It takes into account the nonconformities shown in the product related to the project. The PFMEA should be started with each new process and maintained throughout its life cycle.

"A fully implemented program of FMEA requires an FMEA of process for all pieces/new process, changed, and existing that will be used in new applications or envits." (SAE J-1739, 1995, p.20).

For the tool application, a team composed by 8 people was formed, arranged in the areas that will be affected by the PFMEA:

- PM - Project Manager;
- Engineering;
- PPC - Production Planning and Control;
- Warehouse;
- Production - (Pipe Mounting);
- Quality.

Table 1 (Mcdermott, *et al*., 2009) describes the steps required for PFMEA implantation. 9 steps were followed in the application of the technique with the exception of the ninth. For this one, it was necessary a period of application of improvement actions followed by a new data collection for later comparison.

Table 1 - Steps for the PFMEA implementation.

Steps	Description
1	Process Review.
2	Meeting for bringing up potential failure modes.
3	List the potential effects for each failure mode.
4	Identification of causes and attributions.
5	Indexes attributions – Severity, Occurrence, and Detection.
6	Calculate the Risk Priority Degree for each failure mode.
7	Prioritize the failure modes for acting.
8	Make actions to eliminate or reduce failure modes of higher risk.
9	Calculate the result of the new RPN to check if the value was reduced or eliminated.

Source: Adapted from (Mcdermott, *et al*., 2009).

2.4.1 Step 1: Review of the process

A process flowchart, describing in detail the stages of the process studied, is of great value to aid the understanding of the components of the team (Mcdermott *et al*., 2009). As there was in the shipyard no flowchart to be taken as a basis, it was made contemplating in detail every step of the process.

2.4.2 Step 2: Meeting to raise potential failure modes (Brainstorming)

In this step, the team (composed of representatives from all sectors in which the tool will be applied) met to raise the potential failure modes that may occur during the pipe manufacturing process. To facilitate this survey, we used a well-known and effective method in solving problems in the business environment, the *Brainstorming* (Storm of Ideas).

Is the responsibility of the PPC to control all the hours spent to carry out any task of the productive stages of the ship's construction, it has already stored information on the failures pointed out by the pipe manufacturing sector, only to control the hours spent with the rework. This database contained failure modes of the various sectors involved in the process, so with the data in hand, the team decided unanimously at the first use the information contained in the database, even knowing that there were other failure modes that were not registered, it was decided to attack the failures already known.

Table 2 comes from this database with the history of process failures and shows the frequency of failures and the respective sector where it occurred. When analyzing it, it is possible to observe that were found five distinct modes of failures indicated by the pipe manufacturing for the PPC.

Table 2 - List of Failure Modes with their Respective Frequencies.

Sector where occurred the failure	List of Modes Failure	Qty.	%
Engineering	Miscellaneous reason review	77	32,63%
Engineering	Project Error (conceptual)	63	26,69%
Production – Manufacturing pipe	Incorrect Manufacturing	59	25%
Engineering	Project Error (dimensional)	31	13,14%
Production – Manufacturing pipe	Leak in hydrostatic test	6	2,54%
TOTAL		**236**	**100%**

Source: Author.

2.4.3 Step 3: Listing of potential effects for each failure mode

This step is intended to list the potential effects of the failure mode for each of the situations mentioned in the table of the STEP 2, if it occurs.

> This step should be deepened because this information will be taken into account the assignment of risk classifications for each of the failures. It is useful to think of this step as an "IF-THEN" process, i.e.: IF the failure occurs, THEN, what are the consequences? (Mcdermott, *et al*., 2009, p. 26).

Table 3 lists the possible effects that potential failure modes can cause if they happen.

Table 3 - List of effects for each failure mode.

Failure Mode	Mode Effects
Miscellaneous reason review	Delay of assembly due to the need to carry out the newest revision of the drawing.
	Rework - disassembly and reassembly.
	Rework - disassembly, reassembly and remanufacturing.
Project error (conceptual)	Delay of assembly due to the need to carry out the newest revision of the drawing.
	Rework - disassembly and reassembly.
	Rework - disassembly, reassembly and remanufacturing.
Incorrect Fabrication	Rework - material and man-hour expenditure for remanufacturing.
	Delay of assembly due to the need to realize remanufacturing or reuse of the piece.
Project error (dimensional)	Assembly delay due to incorrect dimensional.
	Rework - disassembly and reassembly.
	Rework - disassembly, reassembly and or remanufacturing.
Leak in hydrostatic test	Rework - material and man-hour expenditure for remanufacturing.
	Rework - material and man-hour expenditure for reuse of the piece.

Source: Author.

2.4.4 Step 4: Identifying the causes of failures

In this step, there is the need to identify all possible causes that resulted in each potential failure mode. According to SAE J-1739 (1995), the way in which the fault can occur is defined as the potential cause of the failure. As SAE J-1739 (1995) indicates, all the mechanisms by which each potential failure can be generated were listed as fully as possible. These causes are listed in Table 4, which was obtained after application of the Ishikawa diagram for each failure mode.

Table 4 - List of Causes for each Failure Mode.

Cause	Failure Mode
Project error - engineering.	Review various reasons
Modification requested by the customer - (improvements).	
Modification of the project requested by the customer - VO (variation order).	
Modification to minimize impact due to on board assembly errors.	
Lack of experience of the workforce.	Project Error (Conceptual)
Lack of compliance with the procedures and analysis of the shipyard's standard documents.	
Lack of compliance with the Assembly Procedures.	Incorrect manufacturing
Lack of knowledge of the workforce.	
Drawing with insufficient information.	
Lack of compliance with the procedures and analysis of the shipyard's standard documents.	Design error (dimensional)
Lack of information from equipment suppliers.	
Wrong information of suppliers of equipment.	
Lack of application of procedures by labor.	Manufacturing defect
Lack of labor experience.	
Bad behavior of the workforce.	

Source: Author.

2.4.5 Step 5: Indexes Assignment - Severity, Occurrence and Detection

In this step, scores were assigned to the indexes severity, occurrence and detection for each one of the potential failure modes. These indexes were taken from standard tables containing criteria that will be correlated with the potential failure modes and then the indexes will be assigned.

According to AIAG (2008), the Severity, Occurrence and Detection ranks must be assigned consistently and in common agreement of the PFMEA team. With the potential failure modes and its effects listed, there was a consensus of the PFMEA team in the assessment of the severity and criticality of the effects caused if the failure occurs, and in this way, the respective severity was consistently applied.

Table 5 demonstrates the assignment of the Severity Index (SI) for the effect of the potential failure modes.

Table 5 - Failure Effect Severity.

Fault Mode	Effect	SI
Miscellaneous reason review	Delay of assembly due to the need to carry out the newest review of the drawing.	8
Miscellaneous reason review	Rework - disassembly, reassembly and remanufacturing.	8
Miscellaneous reason review	Rework - disassembly and reassembly.	7
Project error (dimensional)	Rework - disassembly, reassembly and or remanufacturing.	8
Project error (conceptual)	Rework - disassembly, reassembly and remanufacturing.	8
Project error (dimensional)	Rework - disassembly and reassembly.	7
Project error (conceptual)	Rework - disassembly and reassembly.	7
Project error (dimensional)	Assembly delay due to incorrect dimensional.	6
Project error (conceptual)	Delay of assembly due to the need to carry out the newest revision of the drawing.	6
Leak in hydrostatic test	Rework - material and man-hour expenditure for remanufacturing.	6
Leak in hydrostatic test	Rework - material and man-hour expenditure for reuse of the piece.	5
Incorrect Manufacturing	Rework - material and man-hour expenditure for remanufacturing.	5
Incorrect Manufacturing	Delay of assembly due to the need to perform remanufacturing or reuse of the piece.	4

Source: Author.

As the Severity Index is attributed to the effect caused if the potential failure mode will happen, as shown in table 5, in some cases different Severity Indexes were obtained for the same failure mode, the PFMEA team chose to use the highest assigned index of each failure mode, and thus the table 6 was filled with the Severity Index by failure mode.

Table 6 - Severity Indexes by Potential Failure Mode.

Sector where occurred the failure	List of Modes Failure	Severity Indexes
Engineering	Miscellaneous reason review	8
Engineering	Project Error (Dimensional)	8
Engineering	Project Error (Conceptual)	8
Production Manufacturing of pipe	Leak in hydrostatic test	6
Production Manufacturing of pipe	Incorrect Manufacturing	5

Source: Author.

The occurrence is an index corresponding to an estimated number (sometimes a cumulative number) of failures that may occur; the same must be based in the cause or in the failure mode. (Sakurada, 2001). With the frequencies of occurrence of the calculated failures, a correlation was made between the failure rates and then applied in table 7, and the failure percentages calculated in table 8, were discussed and in a consensus of the PFMEA team were found and assigned the occurrence indexes in a consistent form for each failure mode described in Table 8.

Table 7 - Table of Occurrence Indexes.

Probability of failure	Possible failure rates	Occurrence rate
Very High: The failure is almost inevitable.	≥ 1 in 2	10
	1 in 3	9
High: Generally associated to similar processes previously done that showed frequent failures.	1 in 8	8
	1 in 20	7
Moderate: Generally associated with similar processes previously done that showed occasional failures, but not in larger proportions.	1 in 80	6
	1 in 400	5
	1 in 2.000	4
Low: Associated with similar processes that showed few failures.	1 in 15.000	3
Very Low: Associated with almost identical processes that showed only isolated failures.	1 in 150.000	2
Improbable: Failure is unlikely. Processes almost identical never had failures.	≤ 1 in 1.500.000	1

Source: (SAE J-1739, 1995).

Table 8 - Frequency Table of Failure Mode Occurrences.

List of Failure Modes	Qty	%	Occurrence Index
Revision of various reasons	77	32,63%	8
Project error (conceptual)	63	26,69%	8
Incorrect manufacturing	59	25%	8
Project error (dimensional)	31	13,14%	7
Leakage in hydrostatic test	6	2,54%	6
TOTAL	**236**	**100%**	

Source: Author.

According to Sakurada (2001), the Detection Index (DI) is a value that demonstrates the efficiency of the controls used to detect of the failure (cause or mode of failure), when is the higher the value assigned to the index, greater will be the difficulty of detection. This index can be reduced by adding or improving the technical evaluation of the manufacturing of pipe manufacturing, increasing the size of the samples.

With the association made by the PFMEA team between the potential failures modes found in the process, the detection indexes for each potential failure mode in Table 9 were assigned consistently, and through a team consensus.

Table 9 - Detection Indexes by Failure Modes.

List of Failure Modes	Detection
Miscellaneous reasons review.	10
Project Error (dimensional).	10
Project Error (Conceptual).	8
Leak in hydrostatic test.	10
Incorrect Manufacturing.	3

Source: Author.

2.4.6 Step 6: Calculate of the RPN for each failure mode

The RPN - Risk Priority Number is the product of indexes of Severity (SI), Occurrence (OI) and Detection (DI), (SAE J-1739, 1995). According to Sakurada (2001), this number defines the priority of the failure and is used to classify the deficiencies of the system.

Based on the Severity indexes (SI), Occurrence (OI) and Detection (DI) contained respectively in Tables 6, 8 and 9, was filled in the table 10 and calculated the respective RPN for each potential failure mode through the following relationship: RPN - Risk Priority Number = SI x OI x DI.

Table 10 - RPN Indexes by Potential Failure Mode.

List of Failure Modes	SI	OI	DI	RPN
Miscellaneous Reason Review	8	8	10	640
Project Error (dimensional)	8	7	10	560
Project Error (conceptual)	8	8	8	512
Leak in Hydrostatic test	6	6	10	360
Incorrect manufacturing	5	8	3	120

Source: Author.

2.4.7 Step 7: Prioritization of failure modes for action

In this step, the PFMEA team should evaluate the data obtained by the study and prioritize the failure modes to be attacked as a priority.SAE J-1739 (1995) says that the PFMEA team should focus efforts on the higher RPN in order to reduce the calculated indexes, but not just look at the RPN. In General, independently of the RPN, must pay attention at the severity index (SI) of the effect of the failure.

Due to the small number of Potential Failure Modes found, and in order to achieve greater reliability and reduction of rework in pipe manufacturing and assembly processes, the PFMEA team opted to act at all in an attempt to eliminate or reduce potential failure modes.

2.4.8 Step 8: Action to eliminate or reduce the highest RPN

In this eighth step, the forms to be used to reduce and/or eliminate the identified RPN will be defined and actions will be taken to reduce the Severity (SI) and/or Occurrence (OI) and/or Detection (DI) indexes.

Due to certain peculiarities of the pipes manufacturing and assembling processes in the shipbuilding industry and the failure severity criteria adopted, the PFMEA team judged it to be of very importance to improve detection because, if the failure occurs, it is important that it be identified as quickly as possible preventing delays in construction and delivery to the customer. It is worth noting that for the improvement in detection there was only a reorganization of the processes in the affected sectors, with no new expenses.

Thus, the PFMEA team used the Brainstorming technique again. The team members suggested ideas for improvements and so the actions to be taken to reduce the Occurrence (OI) and Detection (DI) indexes were found and chosen in a consensus. In Table 11 the proposed actions were assigned to their respective Potential Failure Modes.

Table 11 - Improvement Actions by Failure Modes and Their Respective New Indexes.

Failure Mode	Action to be taken
Miscellaneous reason review	1 - Engineering create an emission-review-approval cycle before releasing pipe projects for construction. 2 - Engineering analyze if there is interference in the 3d model, verify that the project specifications meet the ship's order specification before releasing the construction pipe projects.
Project Error (Dimensional)	1 - Engineering create an emission-review-approval cycle before releasing pipe projects for construction. 2 - Engineering analyze if there is interference in the 3d model, verify that the project specifications meet the ship's order specification before releasing the construction pipe projects.
Project Error (Dimensional)	1 - Engineering create an emission-review-approval cycle before releasing pipe projects for construction. 2 - Engineering analyze if there is interference in the 3d model, verify that the project specifications meet the ship's order specification before releasing the construction pipe projects.
Leak in Hydrostatic Test	1 - Recycling course for plumbers. 2 - Requalification of welders. 3 - Intensify the inspections in the pipe plant and the assembly on board. 4- Perform hydrostatic test in the workshop by sampling (30% of spools manufactured in the week).
Incorrect Manufacturing	1 - Intensify the presence of supervisors and inspectors in front of work and instruct plumbers and welders in case of doubt seek them. 2 - Prepare recycling course for plumbers and welders. 3 - Spool release inspections manufactured for the storage yard (supervisor or technician).

Source: Author.

2.5 Results and discussion

After having used the PFMEA technique, it was possible to identify in the pipe manufacturing stages of the naval constructive process that the PFMEA team responsible for its application could not only know its potential failure modes, causes and effects, but also to deepen into the steps that constitute such a process.

Table 2 shows the relationship with the 5 potential failure modes identified in the study. These failure modes are ranked in decreasing order by their respective Severity Indexes and RPN. When comparing the potential failure modes, it was possible to verify that the ones of highest Severity Index found in the study, i.e., SI = 8, are: Miscellaneous Reason Review, Project Error (Dimensional), and Project Error (Conceptual). Thus, it was evident that the first 3 items of Table 12 are the most harmful to the process in case of its occurrence, but the PFMEA team chose to attack all failure modes found.

Table 13 - Potential Failure Modes and their SI and RPN.

Manufacturing Failure Modes List	SI	RPN
Miscellaneous Reason Review	8	640
Project Error (Dimensional)	8	560
Project Error (Conceptual)	8	512
Leak in Hydrostatic Test	6	360
Incorrect Manufacturing	5	120

Source: Author.

In order to enable the visualization of the RPNs behavior, by visual graphic impact of critical elements (Paladini, 1994) of each failure mode, to favor the identification of the points with highest risk index, and to help the decision making of prioritizing in the failure modes solution, the Pareto Diagram was adopted for Fig. 1 composition. After analyzing this graph, it was possible to clearly define which potential failure modes should be attacked aiming to reduce or eliminate the failures in the process.

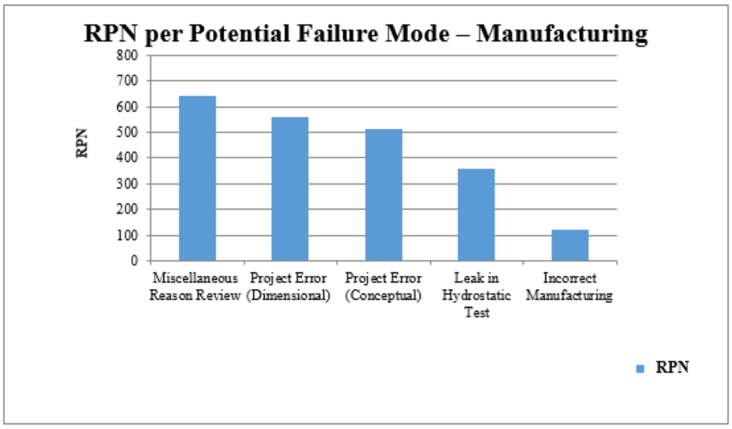

Figure 1 – RPN per Potential Failure Mode – Manufacturing.

Through the data collection and the study of the data previously obtained it was possible to know the causes and effects related to the failure modes studied, and thus the PFMEA team could propose the implementation of improvement actions to reduce or eliminate the RPN of the potential failure modes.

3. CONCLUSIONS

Considering that the PFMEA technique was completely applied in the processes involved in manufacturing pipelines in the yard, it was possible to conclude that this study successfully reached its aims. The results contemplated in this study provide an easy understanding of this technique importance implantation in the manufacturing processes studied.

As evidence, it was possible to observe a considerable improvement of these processes, once the tool facilitated the understanding of each potential failure mode behavior, and the direction of the managerial and operational efforts to minimize or eliminate the risk index.

The use of PFMEA goes beyond simple improvements. The tool ensures a high reliability assuring that the processes will be executed according to the budget, avoiding not foreseen expenses. In addition, it enables the training of the strategic and operational workforce involved in the processes studied, giving greater efficiency in the conclusion of the services contracted to the shipyard, making it more competitive in the world naval market in fact.

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