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APPLICATION OF THE PROCESSES FAILURES MODELS EFECTS ANALYSIS TECHNIQUES (PFMEA) TO THE NAVAL PIPE ASSEMBLY PROCESS

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Abstract. *This paper aims to propose the application of the processes failures modes effects analysis technique (PFMEA) to the naval pipe assembly process of a shipyard located in the port of Suape, state of Pernambuco. The purpose of the application is to identify the main failures in the studied process and the stage in which the highest failure rate occurs with measurement of the impacts caused by them in productivity; verify which of these failures are most recurrent in the process, and enable prioritization of treatment of the major failures according to their criticality and severity. With data analysis, it was possible to prove scientifically that this tool could influence the techniques of assembly the pipes in a positive way, contributing to the continuous improvement of the process and the productivity and quality increase. Based on the results, it was possible to conclude that, by improving the understanding of the behavior of each potential failure mode, through the implementation of the PFMEA technique, there was a better targeting of the managerial and operational efforts to minimize or eliminate the existing risk index in the assembly process of the Pipes.*

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

1. INTRODUCTION

The naval industry is considered strategically important in the world economic scenario because, according to the Construction and Shipbuilding Industry National Trade Union - SINAVAL (2016), about 95% of the world trade is carried out by sea-lanes or waterways (SINAVAL, 2016). In order to supply the demand generated by pre-salt exploration in Brazil, the Brazilian naval industry seeks technologies and strategies that increase its competitiveness in the world naval market. This search is done by increasing productive efficiency, which can be achieved through two strands: increase of productivity itself and/or reduction of production costs.

In order to increase this competitiveness, companies need to identify their process failures and the respective impacts they caused. Through the application of the Process Failure Modes and Effects Analysis (PFMEA) technique is possible to identify the critical points and, from there, to propose effective ways of acting to solve the problem. This solution can consist of a simple change of steps in the process, training of those involved or even the creation of a new system.

This study aims to show that the PFMEA application in the shipyard pipeline assembly process is of extreme importance to ensure the reduction of failures occurrence in the process, reduce rework and give the customer the desired quality. The purpose of these improvements is to become a more competitive yard in the market and with a higher financial return.

2. EXPERIMENTAL PROCEDURE

2.1 Pipes

According to Telles (2001, p.1) are called tubes, closed ducts of circular cross-section, presenting as hollow cylinders. Telles (2001, p.2) also says that in practice pipes are generally and only called rigid ducts, the flexible are sometimes called tubes and more commonly called hoses.

Every industry has pipes of lesser or greater importance and this importance defines the tests by which the pipes will pass in the processes of manufacture and assembly, in a ship the pipes are separated into two classes:

Class 3 - Pipes of minor importance on the ship.

Class 1 - Pipes of greater responsibility of operation.

2.2 Assembly of pipes

The assembly of the pipe whether in industrial works or on board in a ship, is a very complex and important stage for the finalization of the project. It is necessary that the spools be assembled according to the isometric drawings and pipe plants. The isometric indicates the coordinates, in which the spools should be assembled, the specification of the accessories that will be used for assembly and some other information. The pipe plant gives a general layout of the pipe project and what is around it, equipment, platforms, supports etc.

It is necessary that the complete assembly of the piping networks be completed, must be closed the entire path from where the fluid will leave and where it will be taken.

After a network is completely assembled, it will go through the following steps.

- Hydrostatic test (pressure test 1.5 x the project pressure);
- Heating network assembly (*Trace*) - (when necessary);
- Thermal insulation (when necessary);
- Painting (when necessary);
- *Flushing I* Chemical cleaning (wash with: water, oil, chemicals etc.) (when needed).

According to Telles (2001, p. 214) before starting the assembly of any piping system, the respective system equipment (vessels, tanks, reactors, heat exchangers, pumps, compressors, etc.) must be assembled, however, in the day of the construction, it's not that happens because there's no perfect situation at the hands and not to delay the work, the assembly of the pipes is often started from another point of reference until arriving at the equipment.

2.3 FMEA (Analysis of 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 Index, Occurrence Index and Detection Index), 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 ranging between 1 and 1,000 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 Process FMEA (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 environments." (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 Assembly);
- 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 the actions of improvements suggested by this work 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 flowchart of the shipyard piping assembly process was constructed to provide a unique understanding of the process which is being analyzed. The elaboration of such a document was necessary due to the fact that it is essential to use tools that help to understand the process studied (Mcdermott, et al., 2009). The flowchart in question was of great value to help the understanding of the components of the team.

2.4.2 Step 2: Meeting to raise potential failure mode (brainstorming)

The fact that the team of the PFMEA has representatives from all sectors in which the tool will be applied, enabled the survey of the potential failure modes that may occur during the pipe assembly process using the brainstorming technique (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 - Failure modes list with their respective frequency

Setor Onde Ocorreu A Falha	List of failure modes	Qty.	%
Production – Manufacturing pipe	Assembly at the wrong time	248	47,24%
Production – Manufacturing pipe	Interference between disciplines	142	27,05%
Production – Manufacturing pipe	Loss Spool	106	20,19%
Production – Manufacturing pipe	Assembly error	23	4,38%
Engineering	Project error (coordinate)	4	0,76%
Production – Manufacturing pipe	Clogged pipe	2	0,38%
TOTAL		**525**	**100%**

Source: Author

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

With the conclusion of step 2 and the survey of the failure modes to be attacked, starts a very important cycle for the PFMEA, the step of listing the potential failure mode effects if it occurs. So were singled out possible effects for each one of the modes of failure raised in the assembly process.

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

Table 3 - List of effects for each failure mode

Failure Mode	Effects
Assembly at the wrong time.	Rework, disassembly and reassembly.
	Rework, Disassembly, reassembly and remanufacturing.
Interference between disciplines.	Assembly delay due to interference.
	Rework, disassembly and reassembly.
	Rework, disassembly, reassembly and remanufacturing.
Loss spool.	Rework material and man-hour expenditure for remanufacturing.
Assembly error.	Rework, disassembly and reassembly.
	Rework, disassembly, reassembly and remanufacturing.
	Rework, material expenditure and man-hour expenditure for reuse of the piece.
Project error (coordinate).	Assembly delay due to interference.
	Rework, disassembly and reassembly.
	Rework, disassembly, reassembly and remanufacturing.
Clogged pipe	(Man-hour) expenditure for cleaning.

Source: Author

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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
Lack of experience of the workforce.	Assembly at the wrong time
Lack of compliance with the assembly procedures.	
Assembly with dimensions differing from those specified in the drawings.	Interference between disciplines
Project error - engineering.	
Equipment diverged of accessories assembled of the specified in their respective projects.	
Bad behavior of the workforce.	Loss spool
Lack of compliance with the assembly procedures.	Assembly error
Lack of knowledge of the workforce.	
Drawing with insufficient information.	
Assembly with dimensions differing from those specified in the drawings.	Project error (coordinate)
Project Error - engineering.	
Lack of compliance with the assembly procedures and analysis of the shipyard's standard documents.	
Lack of protection at the ends of the pipes.	Clogged pipe
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. According to Sakurada (2001), the Severity index is an indication of how serious the effect of the potential failure mode is, the greater the Severity and criticality of the effect, higher must be the severity index. According to (SAE J-1739, 1995), Severity applies only to the effect of a potential failure mode.

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

Table 5 - Severity indexes for effect of failure

Failure mode	Effect	SI
Assembly at the wrong time	Rework - disassembly, reassembly and remanufacturing.	8
Interference between disciplines	Rework - disassembly, reassembly and remanufacturing.	8
Assembly at the wrong time	Rework - disassembly and reassembly	7
Interference between disciplines	Rework - disassembly and reassembly	7
Assembly error	Rework, disassembly, reassembly and remanufacturing	8
Assembly error	Rework - disassembly and reassembly	7
Interference between disciplines	Assembly delay due to interference	6
Project error (coordinate)	Rework, disassembly, reassembly and remanufacturing	8
Project error (coordinate)	Rework - disassembly and reassembly	7
E Project error (coordinate)	Assembly delay due to interference	6
Loss spool	Rework, material and man-hour expenditure for remanufacturing	5
Clogged pipe	(Man-hour) expenditure for cleaning.	2

Source: Author

As the Severity Index (SI) 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 the failure occurred	List of failure modes	Severity index
Production pipe assembly	Assembly at the wrong time	8
Production pipe assembly	Interference between disciplines	8
Production pipe assembly	Assembly error	8
Engineering	Project error (coordinate)	8
Production pipe assembly	Loss spool	5
Production pipe assembly	Pipe clogged	2

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 indexes occurrence

Probability of failure	Possible failure rates	Occurrence indexes
Very High: The failure is almost inevitable.	≥ 1 in 2	10
	1 in 3	9
High: Generally associated with similar processes that frequently presented failure.	1 in 8	8
	1 in 20	7
Moderate: Generally associated with similar processes that failure 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
Assembly at the wrong time	248	47,24%	9
Interference between disciplines	142	27,05%	8
Loss Spool	106	20,19%	8
Assembly error	23	4,38%	7
Project error (coordinate)	4	0,76%	6
Clogged pipe	2	0,38%	5
TOTAL	**525**	**100%**	

Source: Author

The detection index (DI) can be reduced by adding or improving pipes process evaluation techniques and/or increasing sample size. This reduction is important by the fact that, according to Sakurada (2001), the detection index is a value that demonstrates the efficiency of the controls used to detect the failures (cause or mode of failure), that is, the higher the value assigned to the index, greater is the difficulty of detection.

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

Table 9 – Detection indexes of failure modes

List of failure modes	Detection
Assembly at the wrong time	10
Interference between disciplines	10
Assembly error	10
Project error (coordinate)	10
Loss Spool	1
Clogged pipe	4

Source: Author

2.4.6 Step 6: Calculate the RPN for each failure modes

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 RPNs 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
Assembly at the wrong time	8	9	10	720
Interference between disciplines	8	8	10	640
Assembly error	8	7	10	560
Project error (coordinate)	8	6	10	480
Loss spool	5	8	1	40
Clogged pipe	2	5	4	40

Source: Author

2.4.7 Step 7: Prioritization of failure modes for action

At that moment, it was necessary to prioritize the identified failure modes, defining which would be attacked primarily based on the data obtained by the study.

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

Now begins one of the most important steps of the PFMEA, because it is the moment that the actions to be taken will be defined and they will be responsible for decreasing of the severity (SI) and / or occurrence (OI) and/ or detection (DI), and thus the RPN will be reduced or eliminated.

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
Assembly in the wrong moment	1 - PCP define the exact moment of assembly by analyzing the basic projects and 3D model. 2 - Production supervisor make a second check if the spool can be assembled or not.
Interference between disciplines	1 - Engineering create an emission-review-approval cycle before releasing construction piping projects. 2 - Engineering analyze if there is interference in the 3d model, verify that the project specifications meet the ship's order specification before releasing construction piping projects. 3 - Prior analysis of the supervisor or technician responsible for the work front.
Assembly error	1 - Intensify the presence of supervisors and inspectors in front of work and instruct the plumbers and welders in case of doubt seek them. 2 - Prepare refresher course for plumbers and welders. 3 - *Spool* release inspections assembled on the week (supervisor or technician)
Project error (Coordinate)	1 - Engineering create an emission-review-approval cycle before releasing piping 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 construction piping projects.
Loss Spool	1 - Warehouse release spools only for supervisors. 2 - PCP charge the supervisor that the spool's released for programming will be assembled on board for the week that has been programmed so will be no lost. 3 - Awareness training of the workforce to be more careful with the material.
Clogged pipe	1 - Protect the ends that are open of the spool's already assembly with blind flanges and the spool's that are in the yard to be closed the ends with plastic plugs. 2 - Check if the spools to be assembled are clear.

Source: Author:

2.5 Results and Discussion

With the application of the PFMEA technique to the processes of fabrication and assembly of pipelines existing in the naval constrictive process, the PFMEA team has deepened in the knowing the stages of the process, as well as their potential failure modes, causes and effects.

The six potential failure modes found in the study of the assembly process are listed and classified in Table 2, in descending order by their respective Severity Indexes and RPNs. This table made possible to easily visualize that the first four potential failure modes have high RPNs and the highest Severity Index found in the study, SI = 8. Thus, although the PFMEA team has chosen to attack all failure modes found, these four first potential ones, presented in Table 12, are the most damaging to the process if they happen.

Table 12 - Potential Failure Modes and their SI and RPNs

Assembly Failure Modes List	**SI**	RPN
Assembly in the wrong moment	8	720
Interference among syllabuses	8	640
Assembly error (coordinate)	8	560
Project error	8	480
Spool loss	5	40
Clogged pipe	2	40

Source: Author:

Because it is a tool that uses the visual graphical impact to facilitate the visualization of critical elements [3], the Pareto Diagram with the data of Table 2 was used to create Fig. 1. The intentions were to enable the visualization of the RPN behavior of each failure mode; favor the identification of the points with highest risk index, and help in the decision making of which failure modes should be attacked primarily aiming to reduce or eliminate the failures in the process.

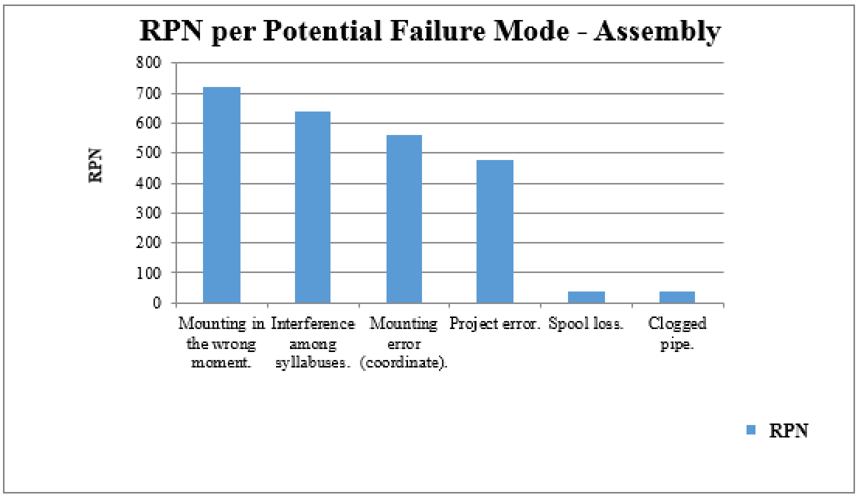

Figure 1 – RPN per Potential Failure Mode – Assembly.

Through the data, collection and the study of the data obtained previously 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

The implementation of the PFMEA technique to the process of assembly naval pipeline in the shipyard had a great importance in its continuous improvement. The tool facilitated the understanding of the behavior of each potential failure mode and the steering of the managerial and operational efforts to minimize or eliminate the risk index. Therefore, this study has successfully achieved its objectives.

Because they are a registry tool, the PFMEA forms, if used, can prevent new failures to happen from the ones registered in them, what ensures not only a high reliability but also the assurance that processes will be executed according to the budget.

Aiming a shorter time of construction or repair of the vessels contracted to the shipyard, the results of this study stimulate two other factors: the implantation of the technique in the other syllabuses involved in the naval construction process and training of the strategic and operational workforce involved in the processes studied based on the material generated by this study.

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