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FAILURE MAPPING PROCESS: AN APPLIED STUDY IN A SHYPYARD FACILITY

Priscila Morcelli Monforte[a]; Ualison Rébula Oliveira[b]; Henrique Martins Rocha[a]

[a] **Rio de Janeiro State University** (UERJ), Brazil
[b] **University Federal Fluminense** (UFF), Brazil

Abstract

Faults represent non-conformities in productive activities. Therefore, approaches to their mitigation are relevant. Risk management techniques enable effective company's strategic planning and the adoption of process controls towards failure reduction and assurance of adequate occupational health and safety. This research purported to integrate four widespread techniques, which are usually applied as stand-alone tools, to provide a robust risk management approach. A literature review about Process Mapping, Preliminary Hazard Analysis (PHA), Fault Tree Analysis (FTA), and Failure Mode and Effect Analysis (FMEA) is provided and their integration feasibility is analyzed, followed by an application study in a shipyard located in Rio de Janeiro State, Brazil.

Keywords: Risk Management; Process Mapping; Preliminary Hazard Analysis; Fault Tree Analysis; Failure Mode and Effect Analysis

1. INTRODUCTION

Failure is an incident in which an item does not perform an intended function (NASA, 1998). Each day, many new materials, new production methods, and management processes are introduced and their effects over large scale production systems are uncertain. Challenges occur in a turbulent backdrop of fierce competition: mergers and acquisitions, new competitors, shorter product lifecycles, regulatory changes, uncertain global economic outlook (Rocha *et al.*, 2014), which triggers an increasing search for ways to improve reliability and eliminate/minimize failures (Pittiglio *et al.*, 2013).

In the product development process (PDP), both quality and product reliability are critical factors for companies searching for successful market positioning (Hallgren *et* Olhager, 2009). Ganghi *et al*. (2014) highlight that companies are struggling with a decrease in loyalty after the recession and eager to avoid a painful race to the bottom of the cost curve in globalized and standardized product arenas.

The increasing need to improve products and services quality, as well as customers' satisfaction, has intensified the use of methods and techniques for process failure mitigation/elimination (Oliveira *et al*., 2012b). While quality provides satisfaction with product and related services, levering customer loyalty and brand awareness, reliability is related to guarantee performance continuity, preventing failures and safety risks (Frank *et al.,* 2014).

As consequence, there is a growing company search for quality, in order to be capable to handle fierce market competitiveness. Consumers are more demanding and, therefore, minimizing failures becomes mandatory. Besides technology fast advancements, human resources development, and continuous process enhancement studies get company constant investments and attention as strategic approach toward failures reduction (Andrade Junior *et* Martins, 2013).

Santos *et al.* (2013) suggest that, for the implementation and structuring of a holistic view, one must identify all the enterprise activities of business. To do so, the Process Mapping technique is a preferred tool: a sector / division work process flow is developed with the intent to visualize the sequence of activities required to deliver a product or service.

Another tool is the Preliminary Risk Analysis (PRA), a structured inductive methodology that, starting from the

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causes and effects, establishes and ranks risks and defines corrective and preventive measures, aimed at preventing the accident in the workplace. The PRA development encompasses six steps: (1) review known problems; (2) review intended purpose; (3) risk assessment; (4) review means of risk elimination and/or control; (5) analyze damage contention methods; and (6) indentify corrective/preventive action responsibilities (Takada *et al*., 2013).

The Fault Tree Analysis (FTA) is a deductive failure analysis in which one can analyze how undesired events (lower-level events) can lead to a system fail (top event). This graphic system model uses a set of logical symbols to identify routs from each event to the top one. Such top down analysis is used to understand how systems can fail, i.e. to identify the cause-effect relationship involving system level (functional) failure and its causes (Flage *et al.,* 2014).

The Failure Modes and Effect Analysis (FMEA) is widely used to define, identify, and eliminate potential system, design, process, or service failures, before they can get to the customers (Ozkok, 2013).

This article main objective is to identify hazards in ship building and, based on the welding process failures, identity existing risks. It is broken down into two specific objectives:

i. A literature review where each of the four techniques concepts are described;

ii. A technique integration feasibility assessment.

A case study is performed in a shipyard facility, located in Niterói, Rio de Janeiro state, Brazil, with the intent to apply and validate the proposed methodology.

The paper is organized as follows: Section 2 examines the research theoretical framework, discussing the concepts of each techniques that will be incorporated in the process of fault mapping; Section 3 analyzes the integration of the four techniques described in the previous section; Section 4 evaluates and validates the proposed procedure in a real application; and, finally, in the Section 5, research findings are discussed and conclusions are presented.

2. FAILURE MAPPING TOOLS AND TECHNIQUES

This section aims to provide a literature review about the four techniques that will be integrated to compose a failure mapping framework.

2.1. Process Mapping

Mapping Process is a graphical modeling process used to provide a better understanding about a process in a sector, department or organization, what helps improving managerial activities (Lee *et al*., 1985).

According Alvarenga *et al*. (2013), the level mapping varies from a process main steps' view, known as macro-level flow, to detailed view, i.e. micro-level flow. It is typically performed through the following steps:

- Identification of products / services and their related processes, identifying start and end of the process;
- Data collection and map preparation;
- Data transcription to the model, followed by identification of bottlenecks, wasteful activities, delays, duplication of efforts, etc.

Through the Process Mapping, existing company processes are questioned, creating opportunities to identifying critical interfaces and to improve organizational performance. It also enables the implementation of new and modern management techniques (Bolsson *et al*., 2013).

Several mapping processes can be used, as the ones listed ahead. Therefore, one must analyze the process and choose the most appropriate technique (Oliveira *et al*., 2010).

- Process Map → documents the process, using ASME symbol set, as shown in Figure 1.

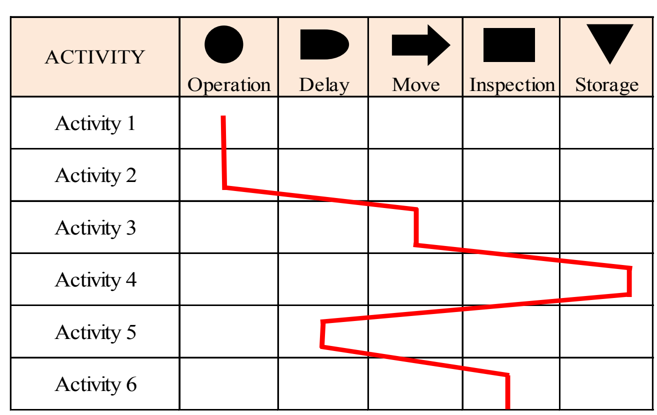

Figure 1: Process Map example

- Flow Process Chart → documents process actions and decision points in a real scenario process, as show in Figure 2.

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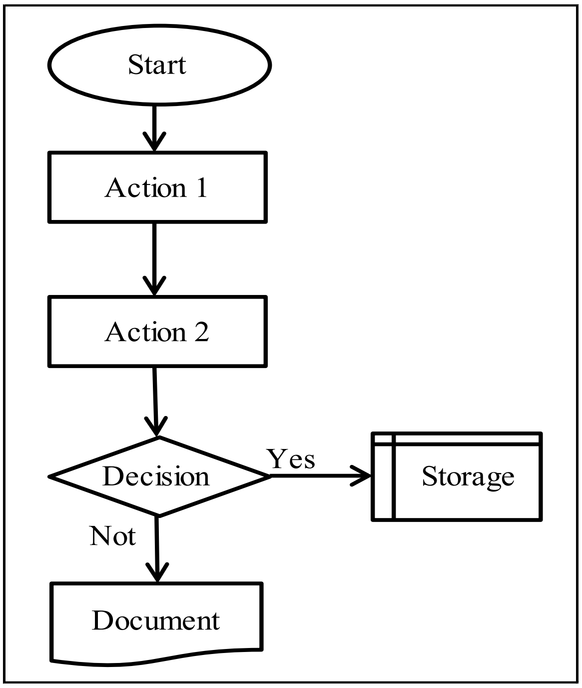

Figure 2: Flow Process Chart example

- Flow diagram → documents the physical route or flow of people, materials, paperwork, vehicles, or communication associated with a process or procedure, as shown in Figure 3.

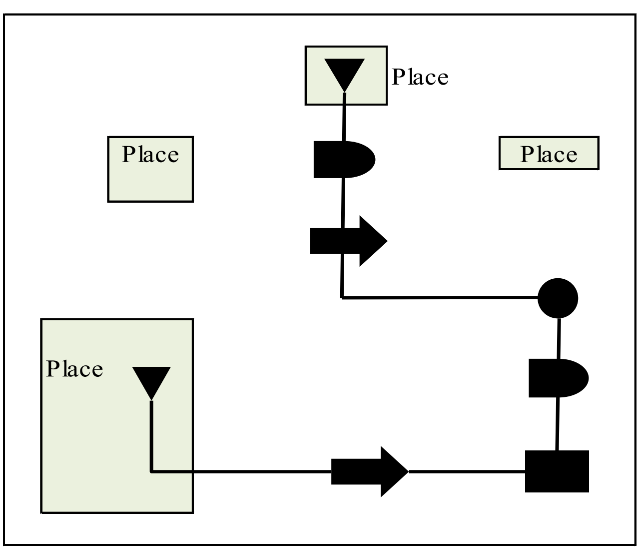

Figure 3: Flow Diagram example

2.2. Preliminary Hazard Analysis

According to Mangili Jr. (2012), the Preliminary Hazard Analysis (PHA) allows the quantification of risk magnitude, so that correction and removal actions can be ranked and prioritized. When applied in the Design and Development phases, it helps the identification and prevention of risks in the operational phase (Sábada *et al.,* 2014).

Sherique (2011) establishes six steps do develop a PHA, as follows:

- Review known issues and search analogies or similarities with other systems;
- Review the mission to which they relate: meets goals, performance requirements, main functions and procedures; establish limits of action and define the system;
- Determine main risks: Points risks which potentially cause injury, loss of function, damage to equipment and materials;
- Review ways of risk removal or control: Investigate possible ways to remove or control risks to establish the best options compatible with the system requirements;
- Analyze damage contention methods: Finds possible and efficient methods for limiting damage caused by risks;
- Indicate who is responsible for corrective and preventive actions: also, assigns activities to be developed in each unit.

PHA results are documented in a spreadsheet, as shown in Figure 4. In each process step, hazards are listed, causes are identified, detection mode and potential effects are described, occurrence frequencies, severity, and risks are quantified, and corrective/preventive actions are established (Viana *et al.*, 2014).

PRELIMINARY HAZARD ANALYSIS						
RISK	CAUSE	EFFECTS / CONSEQUENCES	F	S	R	ACTIONS

Figure 5: PHA Example

2.3. FAULT TREE ANALYSIS

The Fault Tree Analysis (FTA) is a deductive failure analysis, drawn as a graphical representation of a process failure (top event), which is connected to its causes (lower-level events) through top down routes (Long *et al.*, 2000), developing, as described by Dugan *et al.* (2000), a logical tree where events are linked nodes represented by gate symbols, which describe the relationship between input and output events (i.e.: logical operators "and" and "or", as appropriate).

Top and intermediate events are represented by rectangles, while basic events (failure or error in an element

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which causes the problem) are represented by circles. Undeveloped events (which are not possible to know the origin) are represented by rhombuses (diamonds), indicating the end of the process. Figure 5 illustrates this dynamic (Reay *et* Andrews, 2002).

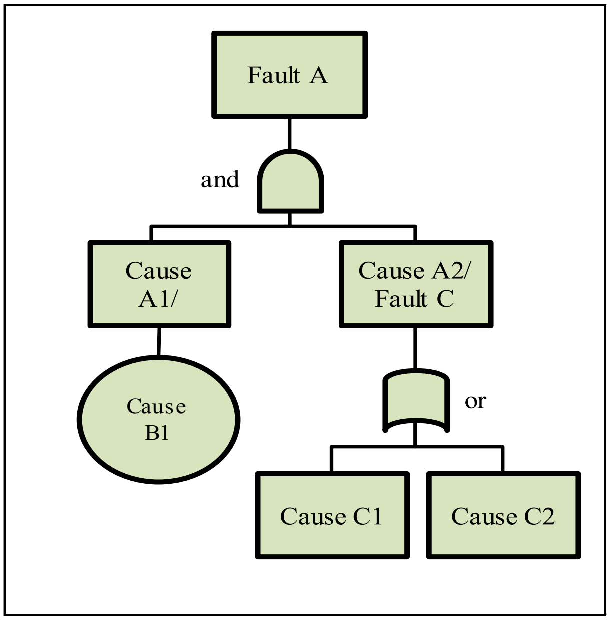

Figure 5: FTA example

In this tool, events are associated with statistical probabilities. Therefore, one can calculate the top event probability, through the use of Boolean logic and several algorithm-based methodologies that ensure efficiency and accuracy in this type of analysis. Since those methodologies are not within the scope of the present article, they will not be discussed.

- Oliveira *et al.* (2012a) propose five steps to perform a FTA:

- Define the undesired (top) event, which is characterized by an abnormal system behavior. It can be inferred from fault reports, mainly those that are directly related to Occupational Safety;
- Obtain understanding of the system, since the analysis of the fault tree requires knowledge of the structure and how it works;
- Draw the fault tree so that all information are integrated and relationship between primary events lead up to the top event;
- Evaluate the fault tree so that a qualitative and quantitative analysis can be performed, so that we know all the causing effects (and probabilities, if possible) of the top event are established;
- Implement actions to increase reliability and to reduce process failures occurrence probability.

2.4. Failure Mode and Effect Analysis

Failure Mode and Effect Analysis (FMEA) is an inductive technique for failure analysis that might occur in Design, Processes, or Systems. Its main objective is to minimize and, if possible, eliminate the associated risks, before failures happen, by anticipating their occurrence. Potential failure modes are identified and the effect of each anomaly on the process performance is determined (Xu *et al.,* 2002).

Data related to fault severity (extent and effects of the occurrence of this failure mode), frequency of occurrence (likelihood of occurrence of a particular failure mode), and detection (potential cause of failure identification capability) are considered for decision making, in order to prevent the occurrence (or the impact) of the event. Figure 6 shows an example of the FMEA form (Garcia, 2013).

FAILURE MODE AND OPERABILITY STUDIES - FMEA									
Start date:			No.:	Responsible:					
Team:			Review:	Prepared by:					
Function	Failure Mode	Effect (s)	Cause (s)	Current controls	S	O	D	RPN	Recommended Actions

Severity of Failure (S)		Occurrence frequency (O)		Detectability (D)	
Noticeable	1	Unlikely	1	High	1
Unimportant	2 a 3	Very Small	2 a 3	Moderate	2 a 3
Moderately serious	4 a 6	Moderate	4 a 6	Short	4 a 6
Serious	7 a 8	High	7 a 8	Very small	7 a 8
Extremely serious	9 a 10	Alarming	9 a 10	Unlikely	9 a 10
Risk Priority Number (RPN): Low 1 a 100 Moderate 101 a 300 High 301 a 1000					

Figure 6: FMEA example

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According Shafiee *et* Dinmohammadi (2014), sometimes the FMEA covers many hierarchical levels. The FMEA process steps are listed down below:

1. Understand the whole process;

2. Identify failure modes;

3. Understanding the effects that the failure modes can cause to the system;

4. Identify the operational and environmental stresses that cause failures;

5. Rate the severity level (S) for each failure in a scale of 1 to 10;

6. Estimate the probability of occurrence (O) for each failure in a scale of 1 to 10;

7. Identify means or methods by which a failure is detected and rank the detection (D) for each failure in a scale of 1 to 10;

8. Calculate the risk priority number (RPN), which is defined as the product of occurrence (O), severity (S) and detection (D) of a failure;

9. Sort the RPN values that are between 1 and 1000 to find faults with higher risks for correction, and RPN values 301-1000 deemed most critical;

10. Sort the RPN in descending order and develop recommendations (preventive or corrective actions) to improve system performance.

3. INTEGRATING TECHNIQUES

The failure identification starts with the application of Process Mapping, being necessary to know the place where the problem is found, what is done through the development of the process flow diagram (Sádaba *et al*., 2014).

The integration of failure analysis techniques is not new: Mahanti *et* Antoni (2005) discussed the use of process mapping with FMEA; Sharma *et al*. (2007) proposed the use of RCA (Root Cause Analysis), NHPPP (Non-homogeneous Poisson Point Process), and FMEA; Shahin (2004) used the integration between FMEA and Kano model; Fernandes *et* Rebelato (2008) used QFD (Quality Function Deployment) with FMEA; Xie *et al*. (2000) suggested the use of Birnbaum's measure and Vesely-Fussel's measure and FTA methodology; Rath (2008) combined Process Mapping with FMEA and FTA; and Oliveira *et al*. (2012b) combined process mapping, expert critical process analysis (ECPA), FTA, and FMEA.

In order to analyze and understand the failures, Oliveira *et al*. (2012a) recommend the use of PHA, FTA, and FMEA, since those techniques provide the necessary information for systems improvements. The PHA prioritizes the Process Mapping task, while the FMEA analyzes each cause of a failure mode and its effect which has been identified in the FTA events. Figure 7 shows the described integration.

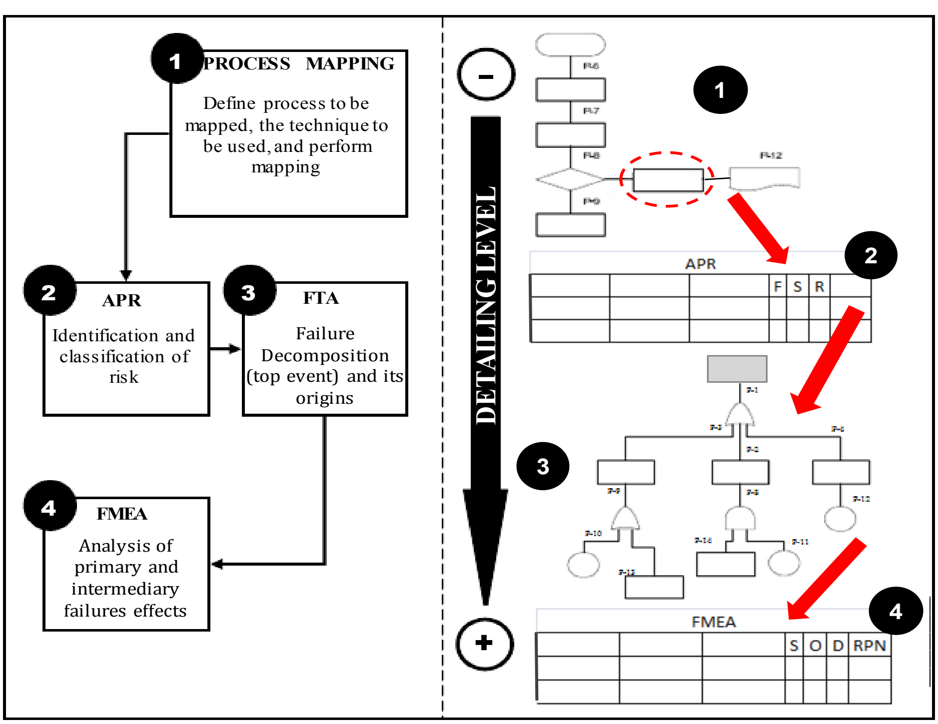

Figure 7: Integrating Process mapping, PHA, FTA, and FMEA

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4. TECHNIQUES INTEGRATION: A SHIPYARD CASE STUDY

To validate the proposed technique integration procedure, we present a case study on a company specialized in offshore oil platform supply vessels (PSV) building. The study focused on the welding process, due to its importance and relevance in the whole shipbuilding process.

The case study methodology, defined by Gerring (2004, p.341) as "an intensive study of a single unit with an aim to generalize across a larger set of units", has been adopted with the intent to investigate the phenomenon (i.e.: the four techniques integration) within its own context (Yin, 2005), which was the application in the shipyard unit, exploring related processes in detail, through data gathering from multiple sources, in order to strengths the theory by triangulation of the evidence (Eisenhardt, 1989).

The shipyard supply chain has been mapped. The flow process chart is shown in Figure 8.

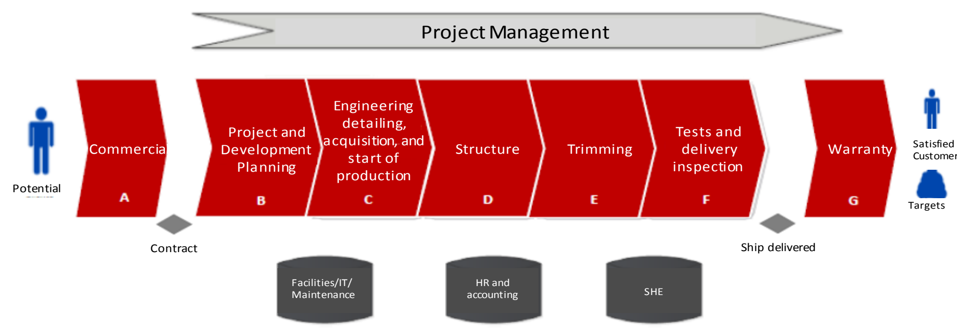

Figure 8: Shipyard flow process chart

The ship structure is block-built: blocks are pre-assembled structural panels built in the hull shop, in berths or dry docks, with the help of heavy duty cranes. Panels are put together forming blocks that in turn are assembled into larger sections that mounted together to become a complete vessel. Welding is necessary to put panels together and, also, to mount the blocks.

As part of the study, Service Orders (SO) have been analyzed, so that failure sources could be tracked and ranked. Collected data has been cross-checked through interviews with the Operations Manager, the shop coordinator, the shift foreman, and some other operations employees. The results converged: the most critical process of the company is welding, as shown in Figure 9.

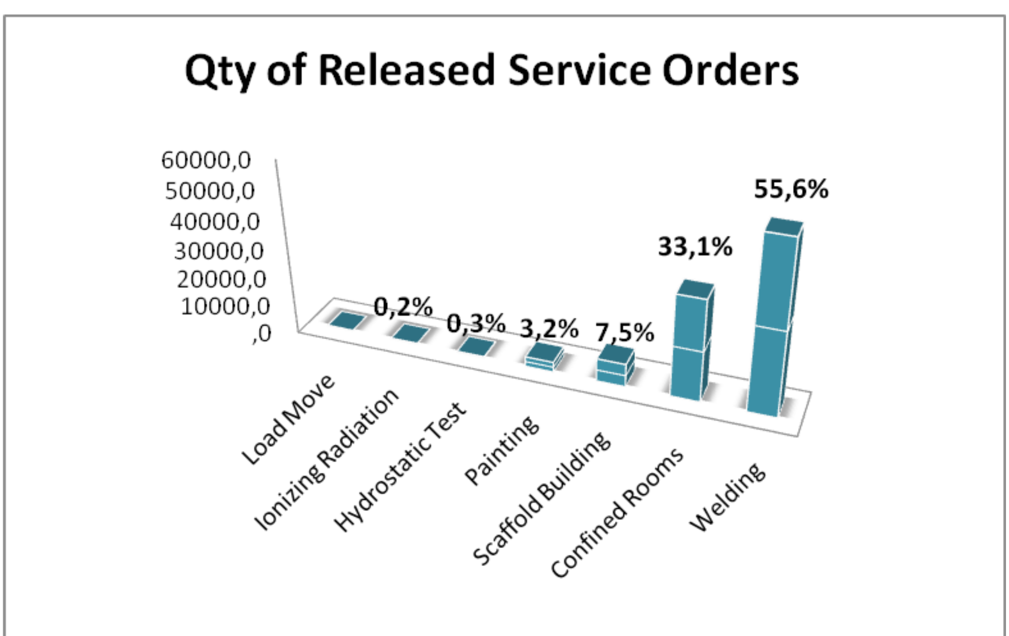

Figure 9: Failures per process

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As a way to determine the risks and preventive measures before operational phase starts, a PHA has been developed by a health and safety engineer, the operations coordinator, a health and safety technician, a welder, and a health and safety intern, with the intent to identify hazards and their possible causes and also to discuss effects and preventive measures.

In addition, severity and consequences, frequency of occurrence, and associated risks have been assessed, so that the information shown in Table 1 could be used as part of the upcoming risk management steps. FTA basic events have been deployed as FMEA items along this process.

Table 1: Welding PHA

PHA - PRELIMINARY ANALYSIS RISK (Welding)							
ACTIVITY	RISK	CAUSE	EFFECTS / INJURY	F	S	R	PREVENTIVE MEASURES / CORRECTIVE / NOTES
Welding	Fall of the same level and level difference	1- depressions in the soil during displacement into the area of activity; 2- imbalance in the displacement of the scaffold.	Fractures, sprains, dislocations, muscle aches and fatal accident.	A	IV	2	Check, when carrying out this activity, the care needed during travel.
	Drop tools, materials and equipment	Tools downside risk, materials and equipment.	Dislocations, edema, fractures and fatal accident.	B	IV	3	1. Inspection and maintenance of accessories and equipment; 2 Correct use of PPE; 3- Guidance supervision; 4- Training of workers; 5- Planning of activities.
	Electric Shock	1- inappropriate PPE, wet or damaged; 2- Lack of training; 3- Failure to use EPC; 4- Lack / maintenance of equipment failure and facilities; 5- Failure of equipment and accessories; 6- Lack of cleanliness and organization (environment).	Burns, unconsciousness and fatal accident.	C	III	3	1 Planning Activity; 2- Training for Workers; 3- Use of appropriate PPE; 4- EPC Adoption (eg Breaker, DR, grounding); 5- Supervision of the activity; 6- preventive and corrective maintenance; 7 Cleaning and organizing the desktop.
	Fire / Explosion	1 Inappropriate use of equipment; 2- Lack of equipment and facilities maintenance; 3- Lack of cleanliness and organization; 4- failure of equipment and accessories (leak torch equipment). 5- hoses and hoses within confined spaces.	Burns, loss of consciousness, damage to heritage and fatal accident.	A	III	1	1 Planning Activity; 2 Signalling area; 3- Training of Workers; 4- Evaluation of EPC adoption of viability; 5- Supervision of the activity; 6 Preventive maintenance; 7 Cleaning and organizing the desktop; 8. Issue of the PSQ.
	Contact with heated surface	1- Lack of use of PPE; 2- Lack of use of EPC (protective barrier and signaling); 3- Lack of activity planning (sobretarefa); 4- failure of equipment and accessories; 5- Lack of training; 6- Lack of cleanliness and organization.	Burn (limbs and body parts)	E	III	5	1 Planning Activity; 2 Signalling area; 3- Training of Workers; 4- Use of appropriate PPE; 5- Evaluation of EPC adoption of viability; 6 Supervision of the activity.
	Contact with contaminated atmospheres	1- Lack of use of PPE; 2- Lack of training; 3- Lack of use of EPC (ventilation and / or exhaust); 4- Lack of cleanliness and organization; 5- Lack of activity planning. 6- Lack of atmosphere verification	Poisoning and Respiratory Diseases	D	III	4	1 Planning Activity; 2- Training for Workers; 3- Use of PPE (Respiratory protection); 4- EPC Adoption (eg ventilation and/or exhaust); 5- Supervision of the activity; 6. Cleaning and organizing the desktop.

The methodology used to identify potential recurring risks of the activities carried out in the operation analysis is a structured inductive PHA task. The studied company process is shown in Figure 10. Based on such document, thermal burning caused by contact with hot surface is the most critical risk within the welding process.

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Frequency categories Occurrence of Scenarios			Severity categories of hazards identified		
Category	Name	Description	Category	Denomination	Description / Features
A	Extremely Remote	Conceptually possible, but extremely unlikely to occur over the lifetime of the process / installation.	I	Negligible	1- No damage or minor damage to equipment, property and / or the environment; 2- do not occur injuries / deaths of employees, third parties (non-employees) and / or people (industry and community); the maximum that can occur are cases of first aid or minor medical treatment.
B	Remote	Expected not occur during the lifetime of the process / installation.	II	Marginal	1- minor damage to equipment, property and / or the environment (material damage are controllable and / or low-cost repair); 2 minor injuries in employees, providers service or community members.
C	Unlikely	Unlikely to occur over the lifetime of the process / installation.	III	Criticism	1. Severe damage to equipment, property and / or the environment; 2 injuries of moderate severity in employees, service providers or community members (remote probability of death); unfolding catastrophe.
D	Likely	Expected to occur dislocated during the lifetime of the process / installation.	IV	Catastrophic	1- irreparable damage to equipment, property and / or the environment (slow or impossible to repair); 2- It causes death or serious injury to several people (employees, service or community members providers).
E	Frequent	Expected to occur several times during the life of the process / installation.			

Figure 10: Company methodology used to interpreter the welding PHA

From this point on, the team had to identify the most relevant errors and their effects and causal (primary failures) of the thermal burning caused by contact with hot surface issue. A FTA has been developed to do so, as shown in Figure 11.

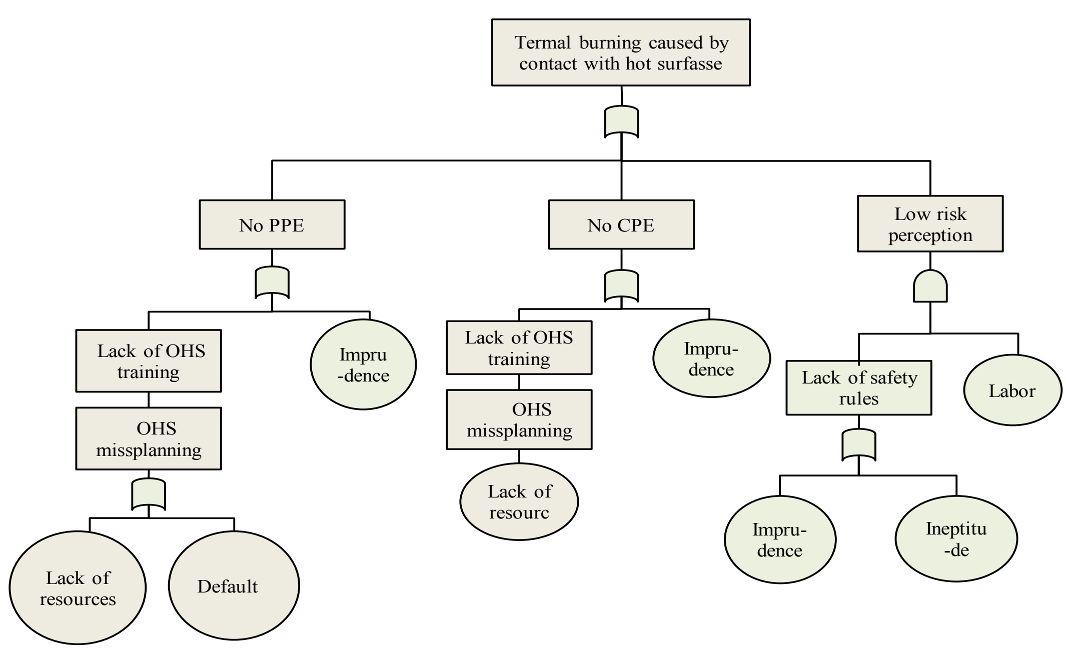

Figure 11: Thermal burning FTA

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It has been detected that even though the Occupational Health and Safety Sector plays an effective role in the prevention and maintenance of physical and mental health, it has to be more proactive regarding the thermal burning issue.

After that, the group developed the FMEA, as shown in Table 2.

Not only the FMEA confirmed the criticality of the welding process in regards to safety issues, but also as a product key-quality element in the shipyard, what had been previously inferred through the other studied techniques.

Besides that, the most critical failure modes have been identified and countermeasures have been established in the FMEA.

Table 2: Welding FMEA

FAILURE MODE AND EFFECT ANALYSIS - FMEA									
Function	Failure Mode	Effect (s)	Cause (s)	Current controls	S	O	D	RPN	Recommended Actions
Block receiving	Delay in the production process	Production interruption	Contractor's delay	Rigor in the Agreement	8	1	1	8	-
			Failed purchasing management	Check List	8	1	1	8	-
Dimensional verification	Measurements out of specification	Delay in the production process	Employee error inspector	Rigor in the Agreement	8	4	1	32	-
			Error responsible for cleaning	Supervision	8	5	4	160	-
Preparation (cleaning) surface for welding	Insufficient cleanliness	Delay in the production process	Error responsible for cleaning	Supervision	7	7	2	98	-
			Failure supervision	Check List	7	3	10	210	-
Welding	Absence of welding	Failure in the final product	Human Error	Supervision	8	3	1	24	-
			Failure supervision	Check List	8	2	2	32	-
	Incomplete welding	Failure in the final product	Human Error	Supervision	8	4	2	64	-
			Failure supervision	Check List	8	4	3	96	-
	Work Accident	Production delays	Failure training	Periodic training	9	8	9	648	Perform daily training
			SESMT Supervision Failure	On-site inspections	9	9	10	810	Hire more technicians in Occupational Safety
			Worker malpractice	On-site inspections	10	10	10	1000	Cotratar psychologists for more effective action with workers
Waste removal (weld cleaning)	No removal of waste	Delay in the production process	Human Error	Supervision	8	4	2	64	-
			Failure supervision	Check List	8	4	3	96	-
Weld Inspection	Inspection Absence	Failure in the final product	Failure supervision	Check List	8	2	4	64	-
	Neglect of inspector	Failure in the final product	Human failure	Meeting with management	8	5	9	360	Tightening up inspections
	Malpractice inspector	Failure in the final product	Failure supervisor training	Absent	8	8	9	576	Promote recycling training for inspectors

5. CONCLUSIONS

This paper presented a study case in a shipyard facility, identifying hazards and faults, in special in the welding process. Initially, four risk management techniques have been described, based on the existing literature, and their potential integration has been assessed.

With the Process Mapping was possible to understand the PSV building process, as well as its critical points. Service orders analysis showed that welding was not just the most meaningful process, but also the most critical in regards to OHS. Then, by employing the methodology in the company studied, it was possible to recognize their critical processes and critical points, in order to prioritize corrective measures and the consequent reduction / elimination of failures.

Through the case study, one can conclude that the techniques' integration is feasible and can provide a guideline to understand processes, to identify critical issues that require actions, and to determine the flaws and its effects, and to establish actions to minimize and, if possible, to eliminate the process flaws.

The method that integrated the Process Mapping with PHA, FMEA, and FTA can contribute to product and process reliability in different organizations and industries.

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It must be noticed that such procedure can only be executed with the support of a multidisciplinary team, so that an anomaly can be studied under different approaches. In this case, the composed of a health and safety engineer, the operations coordinator, a health and safety technician, a welder, and a health and safety intern. Expertise and product / process mastery are critical factor success for this task.

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