FAILURE MAPPING PROCESS: AN APPLIED STUDY IN A SHYPYARD FACILITY

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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, leveraging 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
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 \(\rightarrow\) documents the process, using ASME symbol set, as shown in Figure 1.

![Figure 1: Process Map example](image-url)
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 to 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).

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
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).

![Fault Tree Analysis Example](image)

**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 Effects Analysis Table](image)

**Figure 6: FMEA example**
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
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.

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.
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.

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.
<table>
<thead>
<tr>
<th>Frequency categories</th>
<th>Occurrence of Scenarios</th>
<th>Severity categories of hazards identified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category</td>
<td>Name</td>
<td>Description</td>
</tr>
<tr>
<td>A</td>
<td>Extremely Remote</td>
<td>Conceptually possible, but extremely unlikely to occur over the lifetime of the process / installation.</td>
</tr>
<tr>
<td>B</td>
<td>Remote</td>
<td>Expected not occur during the lifetime of the process / installation.</td>
</tr>
<tr>
<td>C</td>
<td>Unlikely</td>
<td>Unlikely to occur over the lifetime of the process / installation.</td>
</tr>
<tr>
<td>D</td>
<td>Likely</td>
<td>Expected to occur dislocated during the lifetime of the process / installation.</td>
</tr>
<tr>
<td>E</td>
<td>Frequent</td>
<td>Expected to occur several times during the life of the process / installation.</td>
</tr>
</tbody>
</table>

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 10: Company methodology used to interpret the welding PHA](image)

![Figure 11: Thermal burning FTA](image)
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.

Table 2: Welding FMEA

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

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.
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.

6. REFERENCES


