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Quantitative Analysis to Predict Risk of Fire and Explosion in an Energy Company: Case of Study – TechnipEnergies' Matola Yard

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Dissertation submitted to the Chemical Engineering Department of the Eduardo Mondlane University, in fulfillment of one of the requirements for obtaining the academic degree of Master in Health, Safety and Environment, under the supervision of Prof. António Cumbane, *PhD.*

Maputo, August 2022

DECLARATION OF HONOUR

I, Pedro Vuiano Cossa, student of Eduardo Mondlane University, Faculty of Engineering, Master in Health, Safety and Environment, declare on my honour that the work I have developed is original and true, according to the pre-established norms of this educational institution.

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(Pedro Vuiano Cossa)

Maputo, August 2022

To my wife Erjónia Cossa;

To my son and daughter Erik Cossa & Pietra Cossa;

ACKNOWLEDGEMENTS

The realisation of this work was possible thanks to the contribution of various beings who, directly or indirectly, collaborated for its materialisation and helped to overcome the difficulties that arose. Thus, I would like to express my consideration and sincere thanks:

In the first place to "…*God of our Lord Jesus Christ, the Father of glory, may give to you a spirit of wisdom and revelation in the knowledge of him, and that having the eyes of your heart full of light, you may have knowledge of what is the hope of his purpose, what is the wealth of the glory of his heritage in the saints*…" (Efésios 1,17-19)

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LIST OF ABBREVIATIONS

Abbreviation	**Description**
D	Detectability
Cr	Criticality;
O	Occurrence;
S	Severity;
λ	Failure rate;
SWOT	Strengths, Weaknesses, Opportunities, Threats;
FMEA	Failure Modes, Effect Analysis;
FTA	Fault Tree Analysis;
PCA	Principal Components Analysis;
PRA	Preliminary risk analysis;
SVD	Singular Value Decomposition;
NASA	National Aeronautics and Space Administration;
RPN	Risk Priority Number;

ABSTRACT

The objective of this work was to develop a quantitative risk assessment model of fire and explosion occurrence in an offshore logistics facility. Eclectic and oxyacetylene subsystems were analyzed that together make up the hot operation system. The electric subsystem presents as critical components the generator and the compressor, for being the only ones that interact with diesel. The oxyacetylene subsystem is composed only by critical components, because they all interact with acetylene. The class of critic failure modes contain A5 (surrounding heat), A6 (electric spark), A8 (seal leakage) and A9 (impeller leakage) and A10 (compressor tank failure). In this research it was applied Gamma law to modelling the probability of fire and explosion. It was observed that it corresponds to the Beta 2 law. The probability of fire and explosion ranges from 8.06E-07 to 2.73E-04. ISO 3834, which is the international standard for quality requirements for fusion welding of metallic materials, is an excellent strategy to minimize the occurrence of fire and explosion.

Key words: diesel, acetylene, ignition, fire, explosion.

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I. INTRODUCTION

Over the past two decades, a number of serious accidents including the fuel accident have attracted public concerns over facilities safety and reliability. Construction of offshore plants is carried out in harsh environment due to highly concentrated equipment, and a large amount of explosive substances. Hydrocarbon fires and explosions are extremely hazardous in facilities. The fire and explosion will not only result in significant casualties and economic losses, but also cause serious pollution and damage to surrounding environment and terrestrial ecosystems (HSE, 1996). Figure 1 show the fatal occupational injuries in the oil and gas industry, the fire and explosion is present in all the years under study.

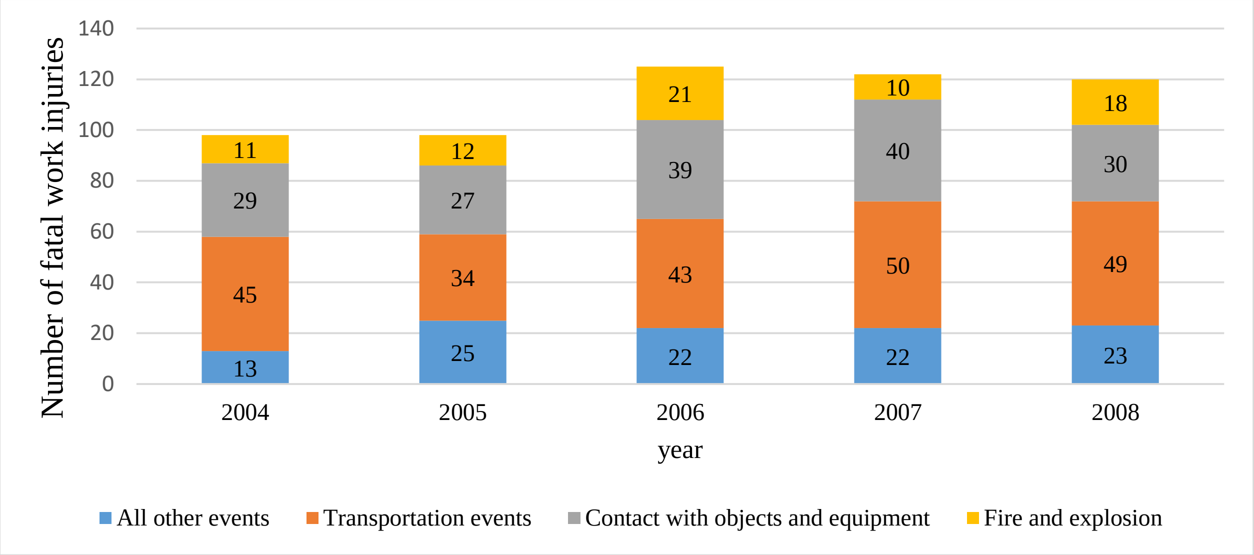


Figure 1. Fatal Occupational Injuries in the Oil and Gas Industry

Source: U.S. Department of Labour (2010)

The quantitative assessment of occurrence of accidents aims to explain the phenomena and events that can occur in the systems, recognizing and exposing its attributes, as well as, defining new relationships between the events involved in the analysis processes. It tries to predict behaviours of the system, not foreseen in the design phases (TANAKA & MELO, 2011).

Safety analysis is performed according to an approach that incorporates the life cycle of the hot work system. The process of design and implementation of technological solutions is called dependability (IRESON, COOMBS & MOSS, 1995). It allows you to place confidence in the choice adopted. Systems safety are part of a process of systems dependability (reliability, avaibility, maintainability and safety).

The present work was carried out at Matola Yard, located in Maputo Province. The system under study requires a large number of resources (human, material, environmental), for its operation. This study takes into account the overall hot operation system. This study took into account the overall hot work system. The system is composed with tow subsystems, the oxyacetylene subsystem is composed of an acetylene cylinder, oxygen cylinder, acetylene cylinder valve, oxygen cylinder valve, flashback arrester of oxygen (before the hose flashback), flashback arrester of acetylene (before the hose flashback), flashback hose of oxygen, flashback hose of acetylene, no-return valves of oxygen, no-return valves of acetylene, flashback arrester of oxygen (after the hose flashback), flashback arrester of acetylene (after the hose flashback). The electric subsystem is composed of compressor, generator, electrode cable, work piece cable, electrode carrier and electrode. Both subsystems are used to heating, welding and cutting metal parts and metallic structures. The associated risk with the diesel and acetylene is a consequence of these flammability properties and high amount of energy released by fire/explosion. In case of fire and explosion, depending on the magnitude, both human, material, and environmental resources can be affected. Several studies propose approaches for risk analysis of fuel fire and explosion (MACINTYRE., et all, 2007).

There are several methods to model the dependability and particularly systems safety, such as Markov chains or Petri net (FISHMAN & CARLO, 1996), Bayesian networks (GROTH, SMITH &. SWILER, 2014). WANG., et all (2015), use a fault tree to model a jet fire in an offshore facility. This study focuses on a risk assessment of fire caused only by internal failures of hot work system during normal operation.

1.1.Problem

Matola yard is an operating center in charge of Technip Energies in Mozambique, is a support facility where part of the logistic process of the Coral South's project takes place. In these facilities the use of fuels (diesel and acetylene) is common during pre-mobilization activities. Figure 2 shows factors that can result in fire/explosion during the pre-mobilization operations in Matola yard.

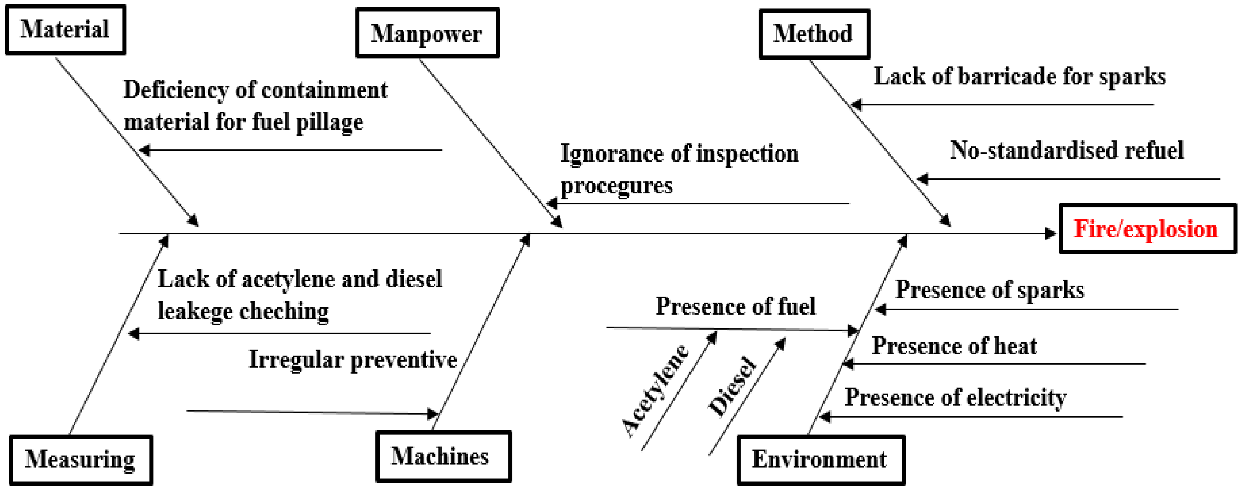


Figure 2. Cause and Effect Diagram

What makes the work insecurity are the lack of inspection of the oxyacetylene station to check possible leakage of acetylene, fuel spillage during refuelling of machine (generator and compressor), and accidental risks difficult to predict as sparks from heating, cutting and welding of metals (Figure 3 and 4).

Figure 3. Spill After Refueling

Figure 4. Sparks Near Acetylene and Diesel

1.2.Justification

The main purpose of "fire and explosion safety in facilities" is to minimize the risk of accident. Risk is understood as the severe or minor exposure of the resources (human and material) contained in the facility to smoke, heat and hot gases. Thus, safety depends primarily on the good conception of the project (ABIMBOLA., et all, 2014).

This study is expected to develop a quantitative risk assessment methodology, capable of proved a foundation for reliability and safety analyses. The application of the proposed methodology will have the ability to map the relationship between faults and operations, establish priorities for the system as a whole, implement changes to the design to decrease risk, make a probabilistic risk assessment and increase compliance with safety standards.

The methodology to be applied in this research is part of the company's scope as a risk management technique, during the fieldwork period there was no evidence that the method applied in this study is used in the company. It is hoped that this research will bring new horizons in the way risk is analysed at the different levels of the operating system, avoiding a scenario identical or worse than what happened at Technip's operational centre in Norway-Lysaker (TPNORGE), where on 12/06/2022 the oxyacetylene station caught fire during the demobilisation of a ship. (Figure 5).

Figure 5. Oxyacetylene Station on Fire

Source: Technip Energies

1.3.Objective

The objective of the study is to perform quantitative risk assessment to predict the occurrence of The objective of the study is to perform a quantitative analysis to predict the risk of fire and explosion in Technip Energies' Matola Yard. For this purpose, the following specific objectives were considered valid:

- Identify failures that can result in fire and explosion in the system, using Failure Modes, Effect Analysis (FMEA), and Principal Component Analysis (PCA);
- Model and study the risk of fire and explosion in the system, using Fault Tree Analysis (FTA);

II. LITERATURE REVIEW

2.1.Preliminary Risk Analysis (PRA)

It consists of the previous study on the existence of risks, prepared during the conception and development of a project in order to detect possible problems that might happen during execution. The qualified professional must perform a risk analysis with the objective of minimizing and/or eliminating all existing risks (STAMATIS, 2003).

In the PRA, the causes that allow the identification of the risks involved in each step of the task are raised, thus, a qualitative assessment of the frequency of occurrence of the accident scenario, the severity and the associated risk is performed (the results are qualitative, not providing numerical estimates). With PRA it is possible to obtain the amplitude of the risk, which through the risk index defines the priority of the risk under study. Thus, after the risk has been prioritised, effective preventive action can be taken (HAQ & LIPOL, 2011).

2.2.Failure Modes and Effect Analysis (FMEA)

In 1949, it was created in the US (Unite States) Army a formal process called "Procedures for Performing a Failure Mode, Effects and Criticality Analysis", which was later called just FMEA (Failure Mode and effects Analysis). In the 1960s, NASA developed this technique as part of the Apollo program, aiming to eliminate failures in equipment that could not be repaired after launch (DAILEY, 2004).

The FMEA is a tool that seeks, in principle, to prevent, through the analysis of potential failures and proposals for improvement actions, the occurrence of failures in the process or product design. The main objective of the FMEA is to prevent problems from reaching the final consumer of the product, system, process or service, seeking to increase reliability, which is the probability of product/process failure. Thus, FMEA provides a systematic method to examine all the ways that a failure can occur (HERPICH & FOGLIATTO, 2013). In this sense, RAMOS (2006) explains that "the FMEA technique was created with a focus on the design of new products and processes, but due to its great utility, it started to be applied in different ways and in different types of organizations".

According MILLER (2006), FMEA it is currently used to decrease the failure of existing products and processes and to decrease the probability of failure in business processes. It has also been used in specific applications such as risk source analysis in safety engineering and in the food industry. This methodology can be applied to both product and process design development. The stages and the way of carrying out the analysis are the same, differing only in the objective.

However, SMITH. (2014), presents other types of FMEA, of which one can highlight the System FMEA, a variation of DFMEA (design FMEA) is carried out to eliminate failures during equipment design, taking into account all types of failures during the whole life-span of the equipment, a variation of PFMEA (process FMEA) is focused on problems stemming from how the equipment is manufactured, maintained or operated, and other variation of SFMEA (system FMEA) looks for potential problems and bottlenecks in larger processes, such as entire production lines. The FMEAs objective is to identify potential failure modes and provide investigative and corrective actions to a service before it reaches the consumer. All are very similar, differing in some points such as the customer, which is not defined as being only the end user, but also the engineers and teams involved in the project/process development.

At the beginning of the FMEA development, the responsible Technical Manager must directly and actively involve representatives from all the areas involved. The FMEA should be a catalyst to stimulate the exchange of ideas between the departments involved and thus promote a team approach. So basically form a group of people who know the product/process in question, its functions, the types of failure that can occur, the effects and possible causes of this failure. Then describe for each type of failure its possible causes and effects, list the measures for detection and prevention of failures that are being, or have already been taken, and for each cause of failure, assign indices to assess the risks and, through these risks, discuss improvement measures (DAILEY, 2004).

One of the main points of the FMEA is the classification of failure modes into "classification items", which define three points: the severity of a failure mode, the detection capability for this failure mode, and the frequency that the failure may occur. The product of these three values creates the RPN (item 20 in figure 5.2), or Risk Priority Number. The function of the RPN is to prioritize the risks with higher chance of occurrence and lower probability of detection. Each project should have customized its own ranking items. Generally, there are two ways that rating items are formulated: Qualitative and quantitative. In both cases, the numerical values can be from 1 to 5 or 1 to 10, with 1 to 10 being the most common form (MOURA, 2000).

One of the FMEA's objectives is to take the necessary actions so that the RPN of all failure modes is lower than 50, considering that 95% confidence is adopted, and that the three classification items are in the 1 to 10 range (HERPICH & FOGLIATTO, 2013).

2.2.1. Severity criterion

Severity is an assessment of the severity of the potential failure mode effect applies only to the effect. Reduction in the severity index can be achieved only through design CHANGE (HERPICH & FOGLIATTO, 2013).

2.2.2. Occurrence criterion

Occurrence is the probability that a specific mechanism/cause will occur. The probability of occurrence has a more important meaning than just its value. The only way to effectively reduce the occurrence rate is to remove or control one or more failure mechanisms through a design change (MOURA, 2000).

2.2.3. Detectability criterion

Detection is an assessment of the ability of the current proposed design controls to identify a design deficiency or the ability of the current proposed design controls to identify the subsequent failure mode before the component is released to production (MOURA, 2000).

2.3.Principal Components Analysis (PCA)

The PCA technique is a statistical tool which aims to describe the variance and covariance structure of a set of variables or dimensions, through linear combinations of the members of this set. Applied over measurement samples in a given system, PCA shows us how and with which importance these dimensions' impact in the measured values variation, frequently explaining hidden relationships between them. Besides that, PCA is a tool used to mitigate redundancy and reduce dimensionality of the set of variables used in system observation through the creation of a new base, whose components are linearly independent and in smaller number, from the main components pointed by PCA among the initial set of dimensions. These new components are ordered in order to maintain the largest portion of the original variance in the first components.

Thus, the principal component (PC) resultant of PCA application represents the axis of the new base with the bigger dispersion of the original data (ANDRECUT, 2009).

2.3.1. Algorithm

According ANDRECUT (2009), the algorithm for applying PCA boils down to the following steps:

1. Organize the measurement data into an n x m matrix, where m is the number of measured variables, or dimensions, and n is the number of samples.

2. If necessary, divide the measurements of each dimension by its standard deviation to normalize them and avoid the sensitivity of PCA to the difference in scale between dimensions.

3. Calculate the covariance matrix of the matrix resulting from the previous steps (if step 2 has been carried out, this matrix will be the correlations matrix).

4. Calculate the eigenvectors and eigenvalues associated to the covariance matrix.

5. Order the eigenvectors according to the associated eigenvalues. This way, the first eigenvector is the principal component, the second is the second principal component, and so on.

6. Discard the less relevant components. For this, define the original variance percentual that must be kept and choose the principal components so that the sum of associated eigenvalues is bigger or equal to this percentual.

There are other similar algorithms to calculate PCA, as the ones which uses SVD (Singular Value Decomposition), a generalization to base swap. These algorithms are so related that PCA is often called SVD and vice versa. For high dimensional data, applying iterative PCA may be a more viable alternative (ANDRECUT, 2009).

2.3.2. PCA results

The PCA, according to JOHNSON & WICHERN (1992), is more a way to reach a final result than a result by itself. This technique is commonly used to reach some objectives as the dimensionality reduction in data sets with many variables applying a transformation for the base formed by the principal components, keeping most of the original variance. Other utility of PCA is explain hidden correlations between variables, through visualizations of the result obtained by applying the technique. This new data presentation can help in data interpretation, by evidencing tendencies, making clear the variables relevance for the original data variance and showing redundancy in the original variables set. Figure 6 illustrates the result of PCA application over a data set.

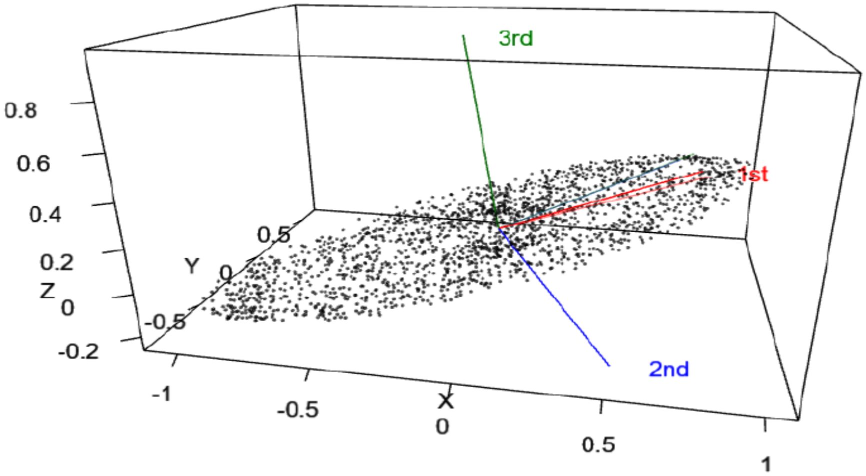


Figure 6. Principal Components Obtained After Applying the Technique on a Data Set.

Source: JOHNSON & WICHERN (1992).

2.4.Fault Tree Analysis (FTA)

The main objective of the Fault Tree analysis technique is to identify the potential causes of failures in a system, which may eventually result from unwanted occurrences. Failures can have various origins, equipment failures, human errors, software errors, environmental conditions are some examples of causes that may lead to the occurrence of the top event defined by the analyst (VESELY., et all, 2002).

A properly constructed Fault Tree, with the various combinations of faults and other events that lead to a particular event, is an illuminating technique of the evaluated system, even for a person who has no knowledge of Fault Trees (VINNEM, 2013).

However, an analyst intending to study a process must, at a minimum, have a thorough knowledge of the operation and functioning of the components of the entire system and also a notion of the failure modes of the components incorporated in the system and the effects that may arise on it. In this way, when building the Fault Tree, system shortcomings can be detected (ABIMBOLA., et all, 2014).

In this context, a fault tree can be used in the design phase of a system to discover hidden failure modes or even in a system in operation to identify weak points and potential failures that can cause accidents. As a result, a list is obtained with the sets of faults that could result in a specific accident. These sets can be classified qualitatively according to the information gathered by the number and nature of the events. Or they can be quantitative results depending on the knowledge of the probabilities of the events happening (VESELY., et all, 2002).

Although often used as a technique that assesses failures, it can also, be used to analyse the success of a system, as stated by (VESELY., et all, 2002).

To be architected by a logic model, the Fault Tree is composed of entities named "gates" whose function is to allow or inhibit the passage of faults to the top event of the tree. In this way, the "gates" indicate the relationship between the events necessary for the occurrence of the top event (PAIK., et all, 2011).

According VINNEM, (2013), as a system analysis technique, the Fault Tree is distinguished from all others by disseminating various information of a process in a single study. These include the following aspects:

a) A detailed knowledge of an entire system or process, identifying all the weak points;

b) Obtaining an estimate of the degree of reliability of a given system;

c) The calculation of the frequency of occurrence of a certain event;

d) Detects potential failures difficult to be recognised by other models;

e) Identifies the basic causes of an accidental event and the most probable failures that contribute to the occurrence of a major accident;

f) Allows detecting maintenance procedures that focus on corrective actions in order to decrease the probability of failures in the system under study;

g) Based on the calculated frequency of occurrence and the most significant contributing failures, it becomes more accessible to take decisions regarding the control of risks associated to the occurrence of a given accident;

h) The possibility of being a qualitative and quantitative analysis of a single system;

According PAIK., et all, (2011), in order for the study to be as detailed as possible, extensive technical and practical knowledge of the whole system under study is required. In this way, and for the construction of a Coherent Fault Tree to be successful, it is recommended that it be structured in eight fundamental steps, as described below.

Step 1 - Identify the Objective of the Fault Tree

The first step was to define the objective of the fault tree analysis, consisting of a problem formulation for the system under study. For the objective to be achieved, it was put in terms of a failure of the system to be analysed, i.e. if the overall objective was to assess the risk of fire and explosion occurring in a system, it was necessary to analyse the whole path of activity and identify the failures that might occur, so that the problem could be avoided.

Step 2 - Define the top event

Once the objective is defined, then the top event in the fault tree is also defined. The top event of the Fault Tree explains how the system fails. The top event defines the failure mode of the system to be analysed. Eventually, the objective may imply the definition and analysis of more than one failure. In these situations, the top events should be defined separately. There are cases, where there may be several objectives and the resulting fault tree can be very different depending on the particular type of objective chosen for analysis. The present study had only one top event (fire and explosion).

Step 3 - Define the fault tree space

In the third step, the analysis space was defined. The action field of the fault tree analysis indicates which of the faults and conditioning factors will be included or not. This action field also includes the space and period of time relevant to the system to be analysed. In short, the space includes the boundary conditions for the analysis, these boundary conditions include the initial states of the materials (components) and the inputs assumed for the system. The analysis space of the study took as relevant human, organizational and technical aspects.

Step 4 - Define the level of detail of the Fault Tree

In relation to step four of the procedure, the resolution of the fault tree analysis is defined, i.e. the level of detail for the fault causing top event to be developed. If the top event is a phenomenological failure, such as a short circuit in a machine that destroys it, its resolution is the level of detail with which the causes of the destruction are modelled. In the case of a quantitative model, its development is based on the need to obtain the best possible estimate for the probability of top events, considering all available data and information.

The purpose of building a Fault Tree is to improve the probability of available faults, i.e., to decrease the probability of existing faults, contributing to greater efficiency. The Fault Tree can, and often is, developed at a level of detail below the level where data is available, to estimate the probability of basic events or where risk discrimination is no longer relevant. In this study every possible scenario that can allow for the interaction of the fuels (diesel and acetylene) with the ignition source (electric sparks and welding sparks) has been taken as detail.

Step 5 - Define the basic rules of the Fault Tree

In step five, any rules that are considered to be basic to the Fault Tree analysis should be defined. The rules include procedures and nomenclatures by which events are named in the Fault Tree. The naming scheme used is very important in creating an easily understood Fault Tree. For example, using illustrated naming schemes, ground rules for the specific modelling of faults in the Fault Tree may be used. The application of these ground rules is due to their usefulness in providing consistency between different Fault Trees, especially when different individuals are developing each one.

Step 6 - Build the Fault Tree

In step six the Fault Tree is built. In this step the events were connected through ports representing the logic present in the system under analysis.

Step 7 - Evaluate the Fault Tree

The next stage, the seventh, is the phase in which the tree is evaluated. The evaluation had two approaches, qualitative and quantitative. In the qualitative assessment information was obtained on the nature of the basic events, which could result from fire and explosion. In the quantitative assessment the probability of each basic event contributing to the top event will be analysed, thus providing the probabilities of a particular event occurring.

Step 8 - Interpret and present the results of the analysis

Finally, the last step is the interpretation and presentation of the results obtained. The results should be broken down to provide information focused on the objective defined for the Fault Tree. In short, the first five stages are the ones that state the problem. In other words, they are the stages in which the top event is defined and how, where and why the process will develop. The remaining three involve the construction, analysis and evaluation of the results. All of them are sequential, except steps 3, 4 and 5 which may be carried out momentarily.

III. WORK PERFORMED

This chapter describes the methodology and methods adopted to conduct this research in order to meet the general and specific objectives mentioned in subchapter 1.3. Table 1 shows the SWOT analysis used in the strategic planning for the implementation of this project.

Table 1. SWOT Analysis

STRENGHTS	WEAKNESSES
• Quality of methodology; • Innovative risk assessment methodology; • Methodology of risk assessment allows a qualitative and quantitative analysis; • Flexibility, precision and adaptability of the methodology;	• Time of practice with the methodology;
OPPORTUNITIES	THREATS
• Methodology is part of the company's scope as a risk management technique;	• Implementation of different risk assessment methodology;

3.1.Data collection instruments

For data collection semi-structured interviews was carried out involving the first line managers of the Matola Yard, as well as the intermediate managers, supervisors and operators, focusing not only on the system, but also on the main risks inherent to the operational chain, which can contribute negatively and interrupt the normal flow of the system under study (see interview guide in Appendix I). Another way of gathering information was by analysing reports provided by the company (Technip Energies), as well as accident statistics for offshore units (OREDA).

3.2.Description of case study

The present work was carried out in Matola Yard, which is located in Maputo Province with address A.v *União Africana* Nr. 4143 - Matola. The Yard is one of the FLNG logistic facilities of the Coral South Project and is owned by Technip Energies (Figure 7).

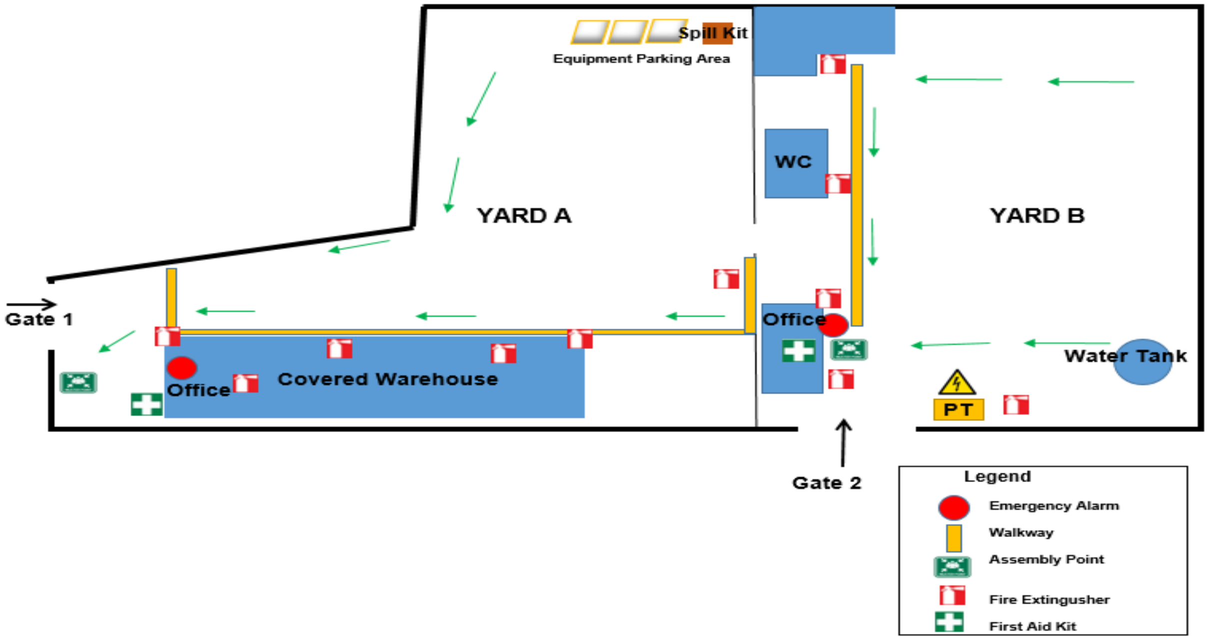


Figure 7. Maputo Yard

Source: Technip Energies

The system under study operates inside Matola Yard, both in Yard A and Yard B. Inside, it can find transportation equipment (Forklift truck, Crane, Telescopics and Trucks), Storage containers, fuels, Equipment and Materials used locally an offshore. Externally, the yard is surrounded by commercial establishments. On normal working days, the Matola Yard receives average of 35 workers. In case of fire and explosion and depending on the magnitude, both the internal and external parts of the yard may be affected.

In the Matola yard, operations associated with the mobilization and demobilization of ships take place. The focus of this research is on the functions relating to the pre-mobilisation phase at Matola yard. The life cycle of hot work during pre-mobilisation is presented in the figure below (Figure 8).

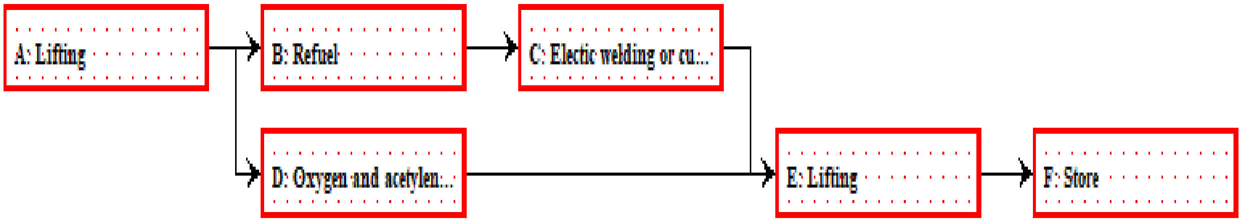


Figure 8. Life Cycle of Hot Work During Pre-Mobilization Activities at Matola Yard (A: Lifting; B: Refuel; C: Electric welding/cutting; D: Oxygen and acetylene cutting/welding; E: Lifting; F: Storage)

3.3. **Mechanical Functions of the system**

It can be observed in figure 6 that the hot work has two phases. They are:

(1) Electric welding/cutting/heating;

(2) Oxyacetylene welding/cutting/heating;

For each phase, there is a group of functions, represented by the letter B (basic) with a numerical index identifying the group. Thus, B1 refers to the group pertinent to phase (1). Level 1 (N_1) functions are those directly linked to a basic function. Level 2 (N_2) functions are those linked to a level (N_1) function. The basic functions linked to hot work are as follows:

(B_1) Perform Electric welding/cutting/heating;

(B_2) Perform Oxyacetylene cutting/welding/heating;

The function (B_1) of oxyacetylene subsystem includes the function (N_1): uses acetylene and oxygen as fuel, uses cylinder valves (oxygen and acetylene) to control fuel flux, uses flashback arrester (before the hose) to avoid the contact of gases (oxygen and acetylene), uses flashback hose (oxygen and acetylene) as fuel conductor (Oxygen and Acetylene), uses the no-return valves (oxygen and acetylene) to avoid mixing of gases (oxygen and acetylene), uses flashback arrester (after the hose flashback) to avoid mixing of gases (oxygen and acetylene), is used for Heating metal parts and structures, is used to welding metal parts and structures, is used to cut metal parts and structures, is used to fabricate metal parts and structures and is also used to recover metal parts and structures.

The function (B_2) of electric subsystem includes the function (N_1): uses the generator to produce electric current, uses diesel compressor to produce electric current, uses electrode cable, uses work piece cable, uses electrode carrier to support the electrode, is used for Heating metal parts and structures, is used to fabricate metal parts and structures, is used to cut metal parts and structures, is used to fabricate metal parts and structures and is also used to recover metal parts and structures.

The loss (announced or unannounced) of the functions (N_1), have possibly catastrophic consequences, because during operation, sparks are generated, in case of interaction with any of the fuels (acetylene and diesel) can cause catastrophic damage not only to the equipment, but also to human lives because the human resources needed for the operation are:

- ✓ 1 supervisor;
- ✓ 5 Welders;
- ✓ 4 Fire watchers;
- ✓ 6 Fitters;
- ✓ 1 NDT Inspector (including MPI set, consumables and report issuance during the shift), attending the last days of mobilization.

3.1.Adaptation of severity (S), occurrence (O) and detectability (D)

For the adaptation of the FMEA used in the evaluation of the risk of fire and explosion, first with recourse to brainstorming preliminary analysis of the system under study was made, also the survey of work procedures and the situation of the equipment involved was made, however the intention was not to exhaust the subject, but to prove that the FMEA is able to identify these risks. MOURA, (2000).

3.1.1. Severity (S)

In turn, the attribution of the severity index in this case study is obtained by determining the degree of impact of the effects of the failure modes on each component of the system. The effects are classified in the following categories: Health and Safety, Environment, Non-Production Costs and Repair Costs. Table 2 below is adapted from the work of HERPICH & FOGLIATTO (2013).

Table 2. Severity index applied to the case study

Effect	Health and Safety	Environment	Severity index (S)
Catastrophic	More than 10 deaths	Of great magnitude and extent, with irreversible damage	10
Critique	From 1 to 10 deaths or permanent incapacitating accidents	High magnitude and difficult to reverse, with risk of irreversible damage	8
High	1 death or permanent disabling accident	Of considerable magnitude and difficult to reverse	6
Moderate	1 accident whith lost time or incapacitating	Of considerable magnitude, but reversible with mitigating actions	4
Low	1 accident without time loss or not incapacitating	Of small magnitude and reversible with immediate action	2
No Impact	No personal injury	No environmental damage	1

Source: HERPICH & FOGLIATTO (2013)

3.1.2. Occurrence (O)

To classify the failure modes occurrence rate, Table 3 below was constructed, according to the FMEA Reference Manual (MOURA, 2000).

Table 3. Occurrence index applied to the case study

Probability of failure	**Occurrence rates in hours**	**Index of occurrence (O)**
Very high: Failure is almost inevitable	≤ 1 in 528 (1 month in operation)	10
High: Frequent failure	1 in 1584 (3 months in operation)	8
Moderate: Occasional failure	1 in 3168 (6 months in operation)	6
Low: Few failures	1 in 5808 (1 year in operation)	4
Very low: Single fault	1 in 11616 (2 years in operation)	2
Unlikely: Failure is unlikely	≥ 1 in 29040 (5 years in operation)	1

Source: MOURA, (2000)

3.1.3. Detectability (D)

In the case of the failure modes detection index classification, Table 4 below was constructed based on the FMEA Reference Manual (MOURA, 2000). To assign the failure modes detection index to the object of study, it was considered that detectability is seen as the ability to detect the failure mode immediately after its occurrence, i.e. the question is whether after the occurrence of the failure mode, the detectability of its cause is immediate, very low or some intermediate level.

Table 4. Detection index applied to the case study

Detectability	**Criteria (probability to detect the failure mode)**	**Index of Detection (D)**
Very Low	Control measures have a very low probability of detecting the existence of the fault	10
Low	Control measures have a low probability of detecting the existence of the fault	8
Moderate	The control measures have a moderate probability of detecting the existence of the fault	6
High	The control measures have a high probability of detecting the existence of the fault	4
Very high	The control measures have a very high probability of detecting the existence of the fault	2
Immediate	It is almost certain that the control measures will immediately detect the existence of the fault	1

Source: MOURA (2000)

After the survey of the fire and explosion risks, identification of the failure modes and definition of the severity (S), occurrence (O) and detectability (D) criteria, the criticality (Cr) was calculated using equation 1. Thus, the FMEA of fire and explosion risk was prepared. The definition of priority order of action for the risks found was performed using Principal Component Analysis. Table 5 shows the FMEA with their respective descriptions.

$$\text{Criticality} = \text{Severity x Occurrence x Detectability} \qquad (1)$$

Table 5. Model of FMEA (S - Severity, O - Occurrence, D - Detection and C_r – Criticality)

Nr	System	Risk description	Causes	Effect	preventive act	S	O	D	C_R	Modification/ Improvement	Undesirable Event
1	Hot work	Release from pump	Lack of maintenance	Fuel release	Maintenance	6	4	4	96	ISO 3834	fire
		Release from Injector	Lack of maintenance	Fuel release	Maintenance	8	4	2	64	ISO 3834	fire
		Tank of generator failed	Lack of maintenance	Fuel release	Maintenance	5	3	4	60	ISO 3834	fire
		Explosion energy	Machanical work	Energy (ignition)	Isolate	7	2	6	84	ISO 3834	fire
		Surrounding heat	Machanical work	Energy (ignition)	Isolate	7	6	7	294	ISO 3834	fire
		Electric spark	Machanical work	Energy (ignition)	Isolate	9	9	9	729	ISO 3834	fire
		Casing of compressor	Lack of maintenance	Fuel release	Maintenance	6	4	6	144	ISO 3834	fire
		Release from seal	Lack of maintenance	Fuel release	Maintenance	7	4	7	196	ISO 3834	fire

		Release from impeller	Lack of maintenance	Fuel release	Maintenance	6	5	7	210	ISO 3834	fire
		Tank of compressor failed	Lack of maintenance	Fuel release	Maintenance	8	7	7	392	ISO 3834	fire
		Cylinder failed	Lack of maintenance	Fuel release	Maintenance	5	2	7	70	ISO 3834	fire
		Cylinder valve failed	Lack of maintenance	Fuel release	Maintenance	6	5	3	90	ISO 3834	fire
		Flashback arrester failed	Lack of maintenance	Fuel release	Maintenance	4	3	4	48	ISO 3834	fire
		Flashback hose of failed	Lack of maintenance	Fuel release	Maintenance	5	4	3	60	ISO 3834	fire
		No-return valves of failed	Lack of maintenance	Fuel release	Maintenance	4	2	5	40	ISO 3834	fire
		Flashback arrester of failed	Lack of maintenance	Fuel release	Maintenance	3	4	4	48	ISO 3834	fire

3.4.FMEA Application

3.4.1. Principal Component Analysis (PCA)

In this work, a simulation program was developed using the MATLAB version R2015a.

3.5.Fault trees of fire and explosion event

3.5.1. Mechanical characteristics of the system

Fire can occur by the interaction between the fuel (diesel or acetylene) and the different ignition sources (Figure 2). In this scenario the safety measures do not protect this failure. Additionally, diesel can be found in the generator and the compressor. Acetylene can be found in the cylinder that makes up the oxyacetylene system. Ignition can be generated by electric spark, explosion energy and external heat from surrounding. In the design process, the fusion of the two subsystems under study (electric and oxyacetylene) will considered. The detailed scenarios are analyzed using root causes as shown in Figure 9.

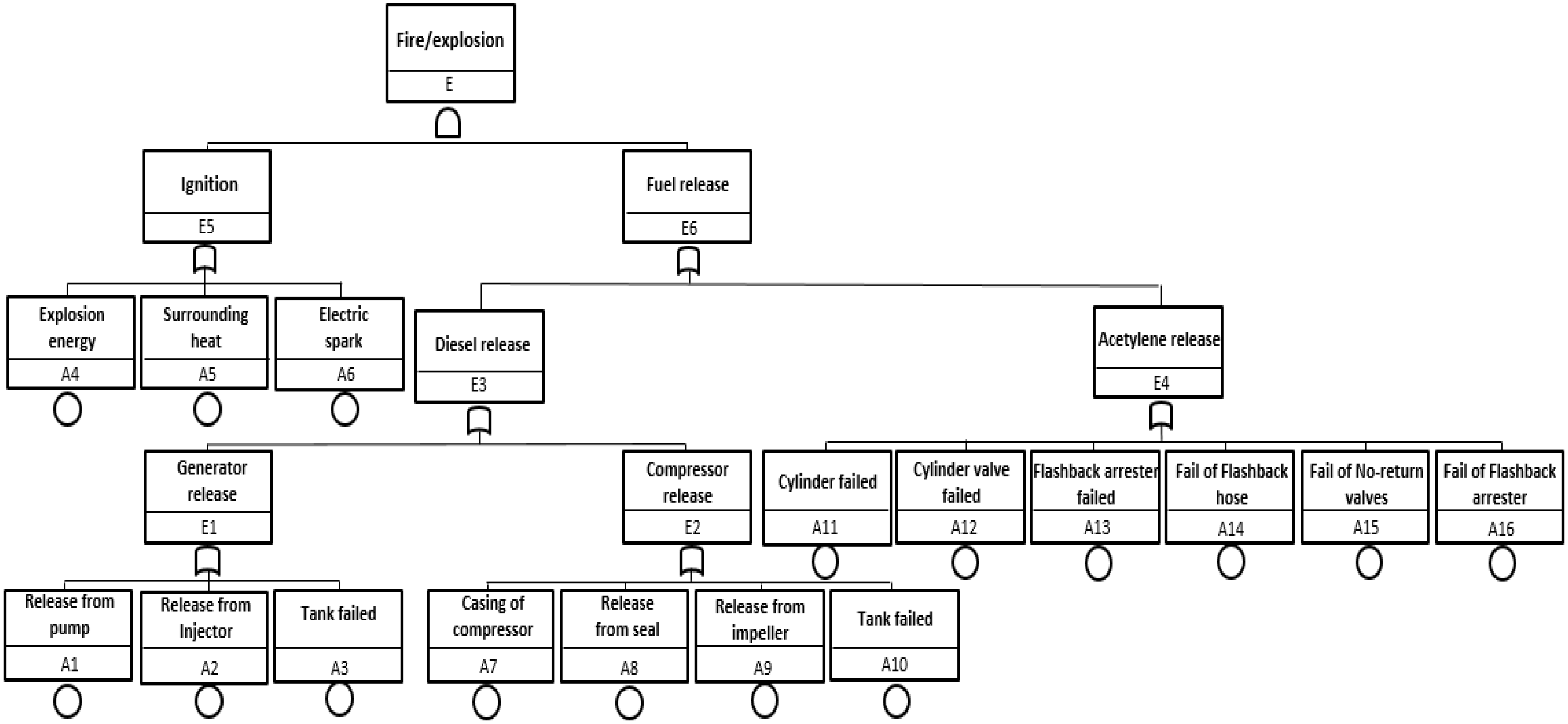
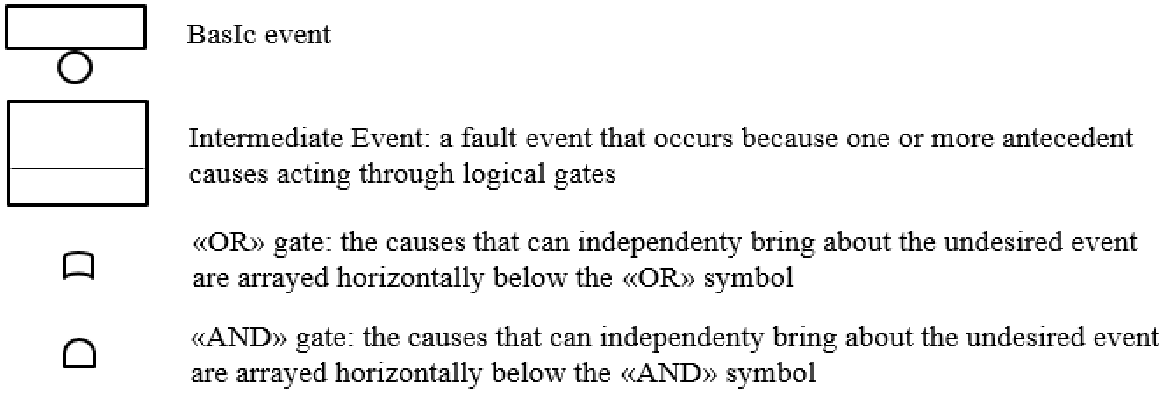


Figure 9. Root Cause (A13: Before the Hose Flashback, A16: After the Hose Flashback)

Legend:



BasIc event

Intermediate Event: a fault event that occurs because one or more antecedent causes acting through logical gates

«OR» gate: the causes that can independenty bring about the undesired event are arrayed horizontally below the «OR» symbol

«AND» gate: the causes that can independenty bring about the undesired event are arrayed horizontally below the «AND» symbol

3.6.Fault tree applications

In this research, the fault tree was built in two steps: First, the fault tree of the system under study was built based on the root cause technique according to WANG (2015). Then, according to the same author, the probabilistic modeling of the events that compose the fault tree was performed. The simulation was develop using MICROSOFT EXCEL

3.6.1. Failure rate and probability data

Probability of events was modelled from component failure rate. These are defined by the average of failure rate (Failure rate Mean (λ_{mean}), by a 90% uncertainly interval for the minim failure rate (Failure rate Lower (λ_{min}), Failure rate Upper $\lambda(_{max})$, and by standard deviation of failure rate (Failure rate SD (λ_{SD}). The data come from the offshore reliability data (OREDA, 2002). Some specific data could be found in WANG (2015), study. Different databases will be used because of the limited data for components that are specific to the system under study.

3.6.2. Probabilistic modelling of the fault tree events

The objective of this section is to present the probabilistic approach applied on data of event tree. Given that the top event (or feared event) is the fire and explosion, the calculation is to assess the probability that the fire and explosion occurs at later time t. Thus, substantially all of the events are presented in the same time scale. Monthly the hot work operation is supposed to support 336 h. To ensure the quality of statistical results, 1000 simulations are performed. Thus, each simulation corresponds to a cycle. Simulations results are presented for 1000 potential cycling of 336 h.

In the present work, the global fault tree of the fire and explosion is simulated 1000 times in potential cycling conditions.

To avoid a very severe and pessimistic scenario due to the application of the exponential probabilistic model, in this study a realistic distribution model is used. In this study it was applied a Gamma Law as probabilistic model used to describe the random distribution of a mechanic components involved with fuel release and ignition. Table 7 show the data used to modeling the probability of fire and explosion.

Table 7. Events Data

Label	Basic event	Failure rate lower	Failure rate mean	Failure rate upper	Failure rate sd
A1	Release from pump	0	0.000739	0.004133	0.002016
A2	Release from Injector	0	0.000739	0.004133	0.002016
A3	Generator tank failed	0	0.000739	0.004133	0.002016
A4*	Explosion energy	0	0.001	0.002	0.001
A5*	Surrounding heat	0	0.02	0.021	0.001
A6*	Electric spark	0	0.025	0.026	0.001
A7	Casing of compressor	0.000034	0.005443	0.020765	0.007661
A8	Release from seal	0.000034	0.005443	0.020765	0.007661
A9	Release from impeller	0.000034	0.005443	0.020765	0.007661
A10	Compressor tank failed	0.000034	0.005443	0.020765	0.007661
A11	Cylinder failed	0.000101	0.00084	0.002218	0.000706
A12	Cylinder valve failed	0.000101	0.00084	0.002218	0.000706
A13	Flashback arrester failed	0.000101	0.00084	0.002218	0.000706
A14	Flashback hose of failed	0	0.000202	0.000638	0.000235

A15	No-return valves of failed	0.000101	0.00084	0.002218	0.000235
A16	Flashback arrester of failed	0.000101	0.00084	0.002218	0.000706

Source: OREDA, (2002); * - WANG (2015)

3.6.3. Gamma distribution

The standard form of the probability distribution is expressed as follows:

$$f_x(X) = \frac{a^p}{\gamma(p)} X^{p-1} e^{-aX} \qquad (8)$$

With $X \geq 0$,

$$\gamma(t) = \int_0^\infty e^{-u} u^{t-1} du \qquad (9)$$

$\boldsymbol{a}$ and $\boldsymbol{p}$ are the shape parameters of the probability distribution. They are expressed in terms of the mean ($\boldsymbol{m_X}$), and standard deviation ($\boldsymbol{s_x}$) of the random variable (X).

$$a = \frac{p}{m_x} \qquad (10)$$

$$p = \frac{1}{{v_X^*}^2} \qquad (11)$$

For the distribution we adopted $0{,}1 < Cov < 0{,}2$ because it is considered realistic. It was applied a confidence level of 95%. Figure 10 show the procedure for reliability analyses.

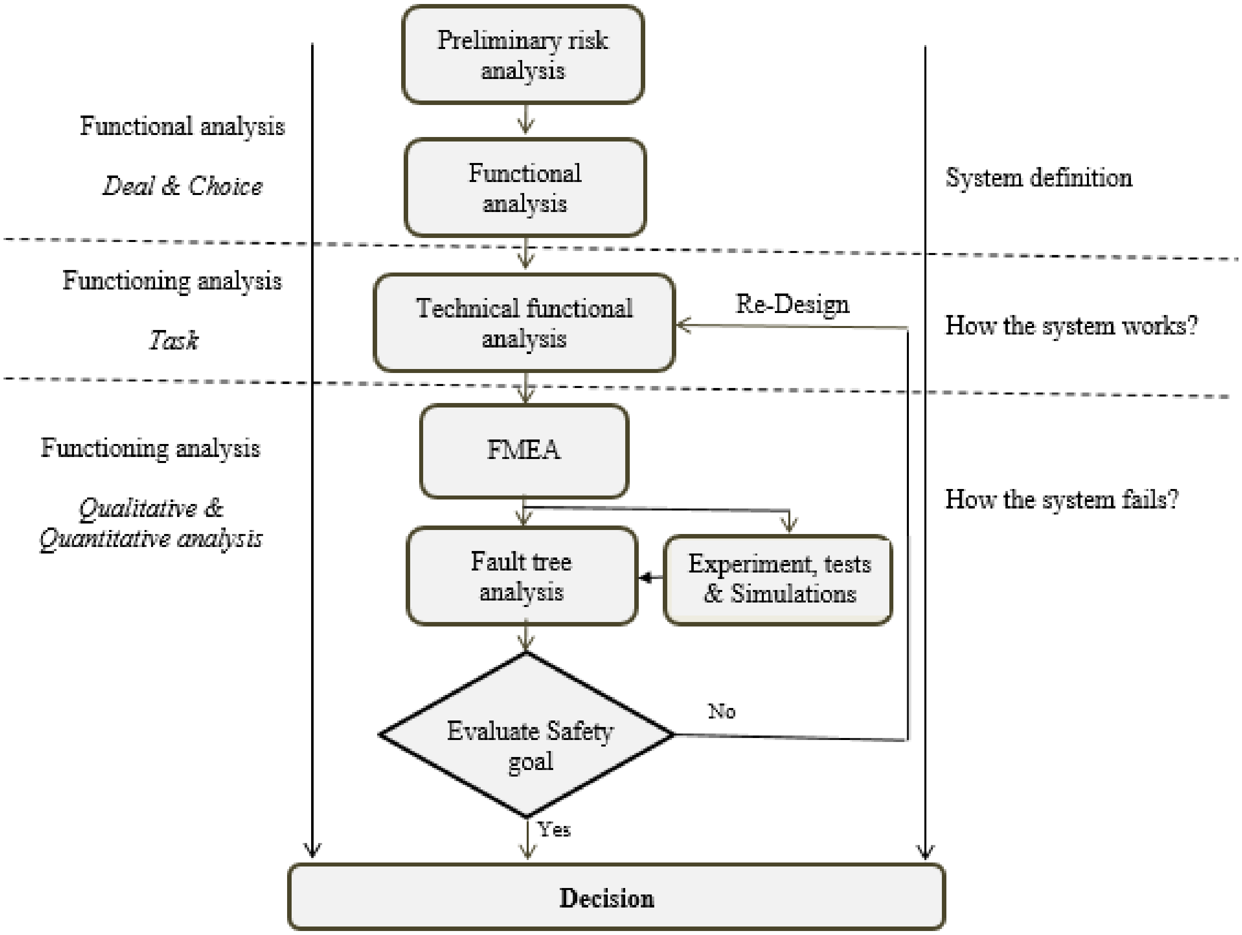


Figure 10. Procedure for Reliability Analyses

IV. RESULTS AND DISCUSSION

4.1.Principal Component Analysis (PCA)

Figure 11 presents the eigenvalues of an axis in the new projection space, which reflects the dispersion of the observations. The amount of information formed by the plan of the first factorial axes (axis 1 and axis 2) is 89,70%.

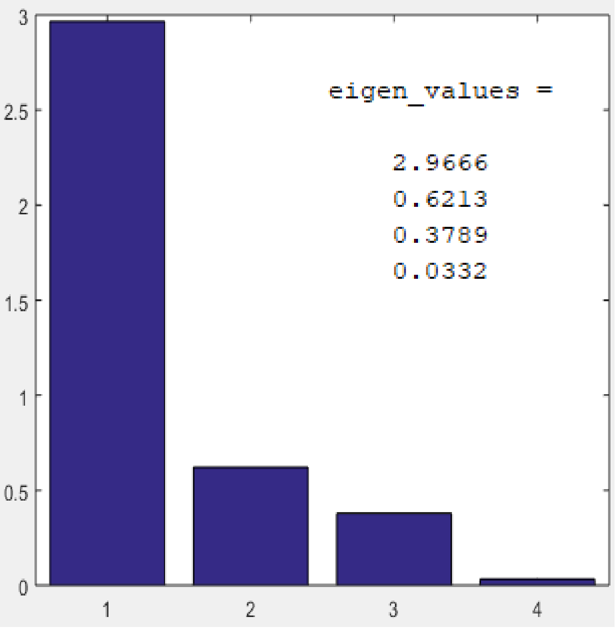
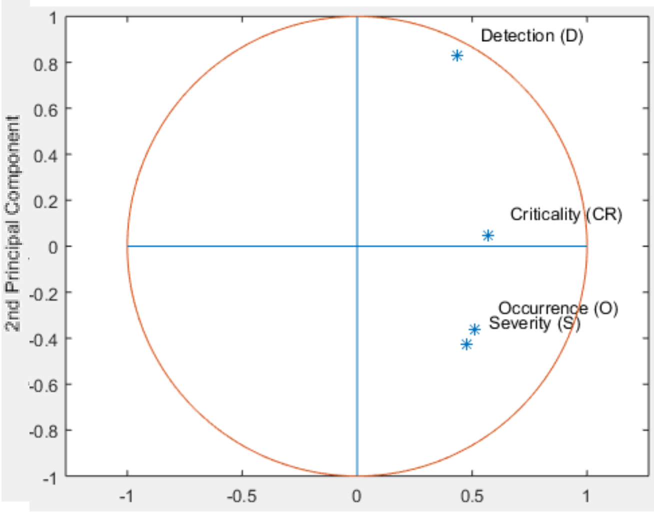


Figure 11. Eigenvalues

Figure 12 and Figure 13 is the geometric representation by affinity of the variables and failure modes. For the first factor, the variables severity, occurrence, detectability and criticality are positively correlated with each other. For the second factor, the variables detection and criticality are positively correlated, while the variables severity and occurrence are negatively correlated.



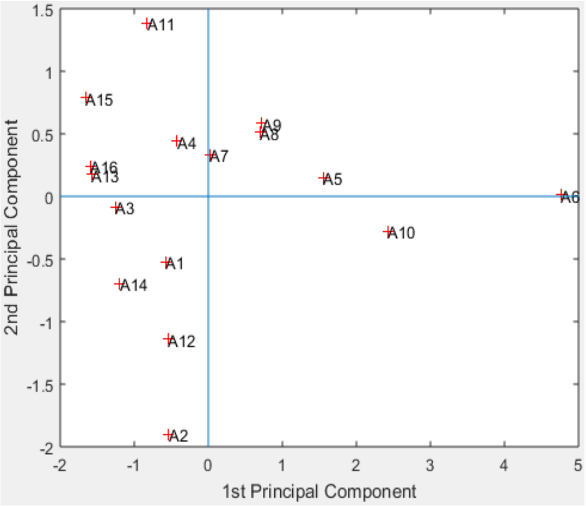


Figure 12. Variables in 2D

Figure 13. Failure Modes in 2D

4.1.1. Silhouette

Figure 14 shows the grouping of the individuals into classes. This silhouette shows that point in first class have a large silhouette value, greater than 0.5972 indicating that this class is significantly separated from the other neighboring class. In the new plane formed by the first two principal components, the failure modes contained in the critical class are: A5 (surrounding heat), A6 (electrical spark), A8 (seal leakage) and A9 (impeller leakage) and A10 (compressor tank failure), because are close to the all variables (severity, occurrence, detectability and criticality) (Figure 12 and 13).

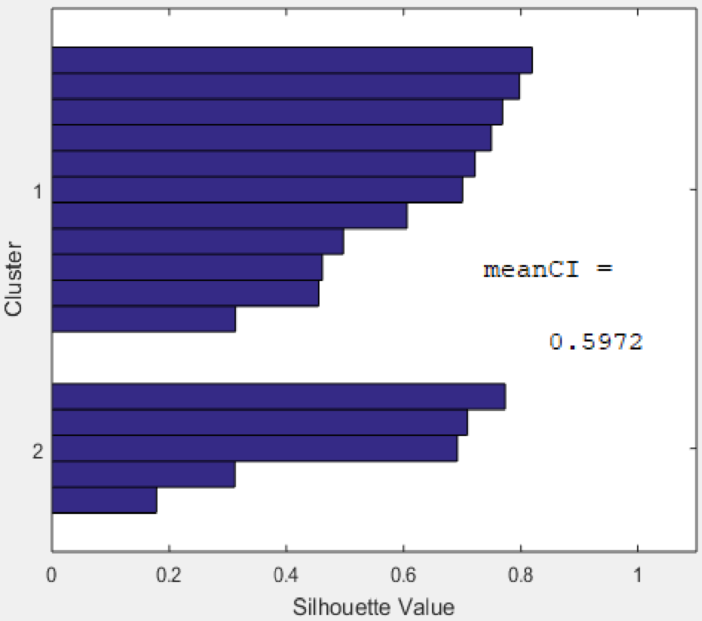


Figure 14. Silhouette

4.2.Beta 2 distribution

Figure 15 shows several shape of the probability distribution in function of p and a. This type of probability distribution is used for random loads that are physically defined between two limits. Both limits must be of the same order of magnitude. Its limits ($a = \lambda_{min}$ and $b = \lambda_{max}$), its mean($\lambda mean$), and dispersion($\lambda mean/\ \lambda_{SD}$) are given by the databases on the failure modes studied. Most studied failure modes look like 3rd curve ($f_x(x)p = 20; a = 5$).

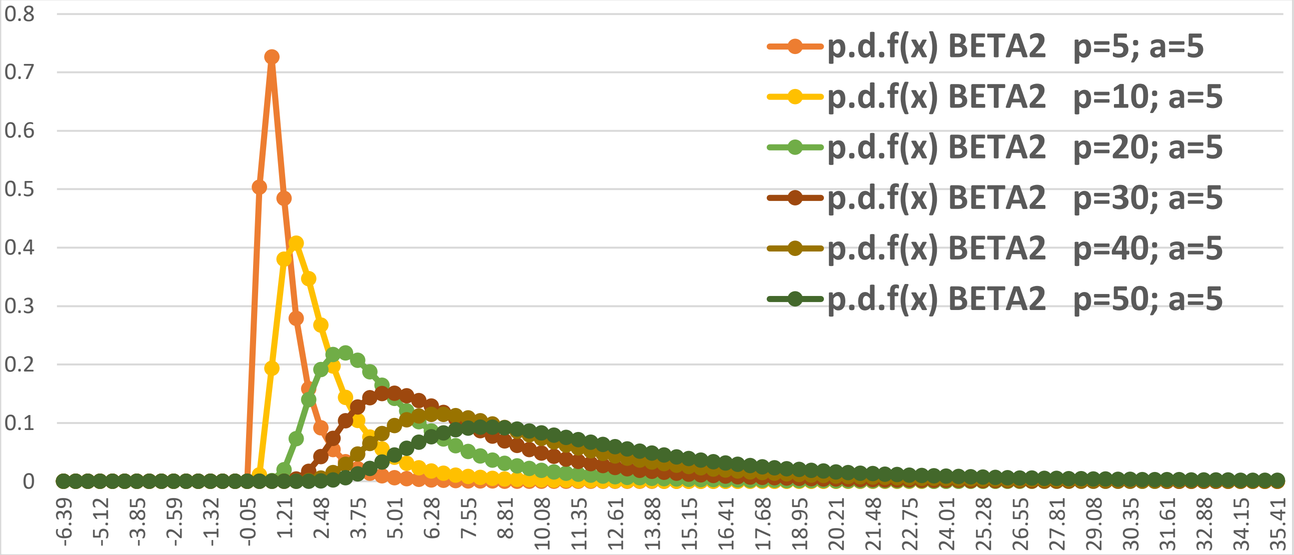


Figure 15. Probability Density Function for Beta 2 Distribution

4.3.Probability of intermediate events

Figure 16 shows a realistic probabilistic estimation of diesel spillage from the generator and compressor. The generator spillage probability ranges from 1.02E-04 to 9.70E-03, and the compressor spillage probability ranges from 7.76E-05 to 1.19E-02.

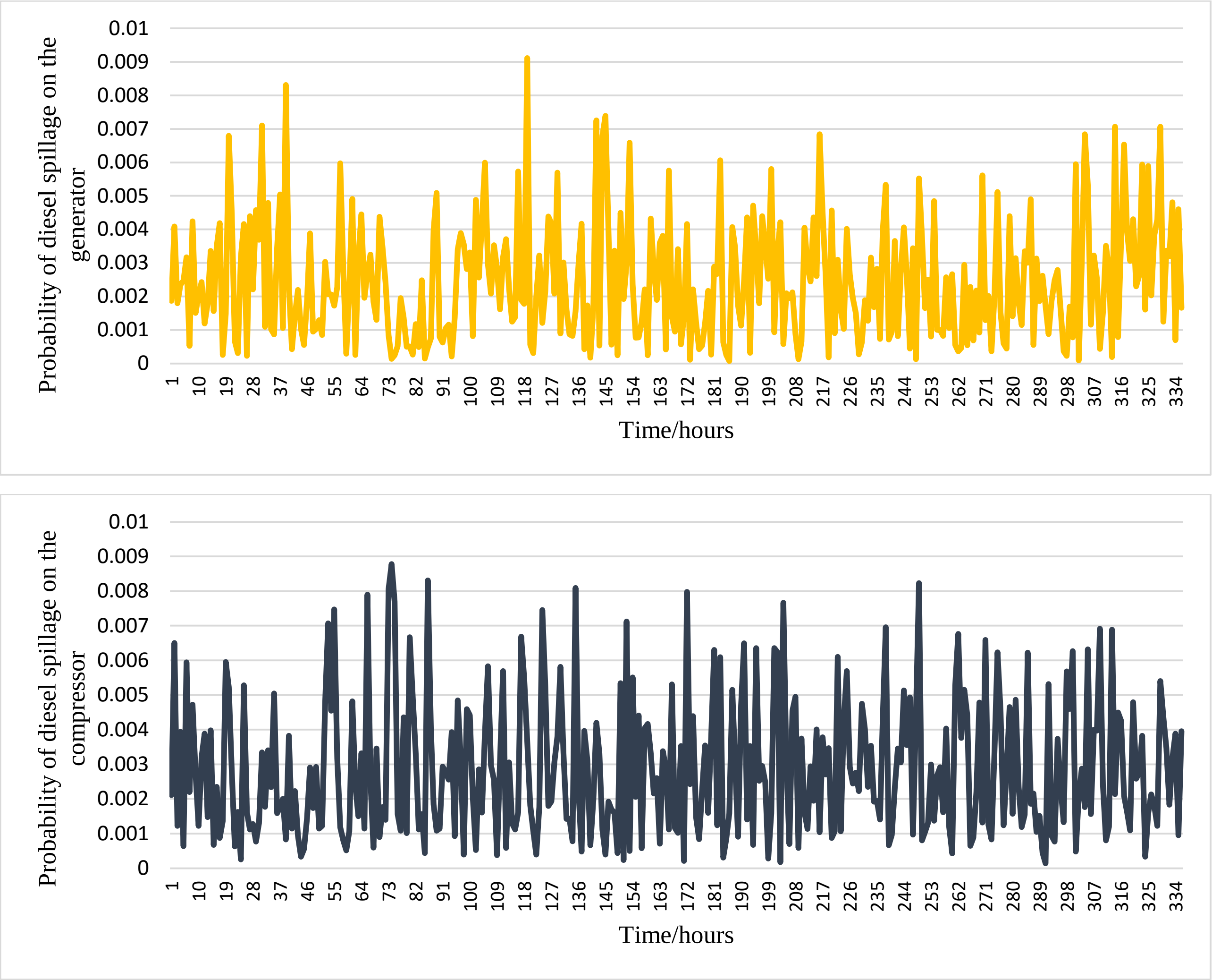


Figure 16. Probability of Generator and Compressor Spillage

From the probability of critical components (generator and compressor) of the electrical subsystem, it was estimated the probability of diesel spillage, which ranges from 4.75E-04 to 1.36E-02. From the probability of the critical components of the oxyacetylene system, the probability of acetylene spillage was estimated, ranging from 8.15 E-04 to 2.67E-02 (Figure 17).

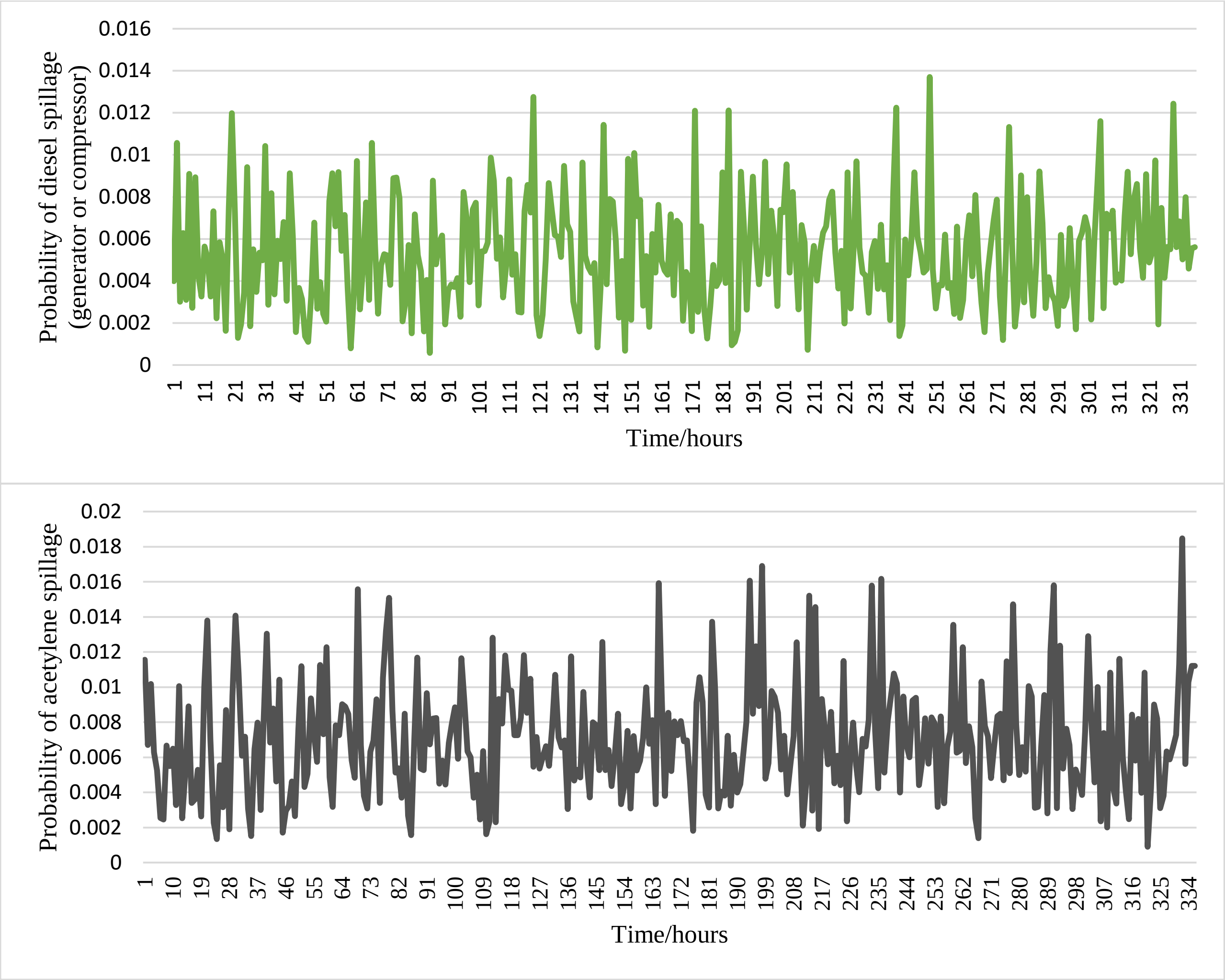


Figure 17. Probability of Diesel and Acetylene Spillage

Globally, the probability of fuel spillage (diesel or acetylene) ranges from 2.36E-03 to 3.40E-02 (Figure 18). The basic event that contributes the most to this occurrence is A10 (compressor tank failure), since it has the criticality value of 7. The probability of ignition ranges from 1.33E-04 to 1.94E-02. Table 8 present more details about the probability of intermediate events.

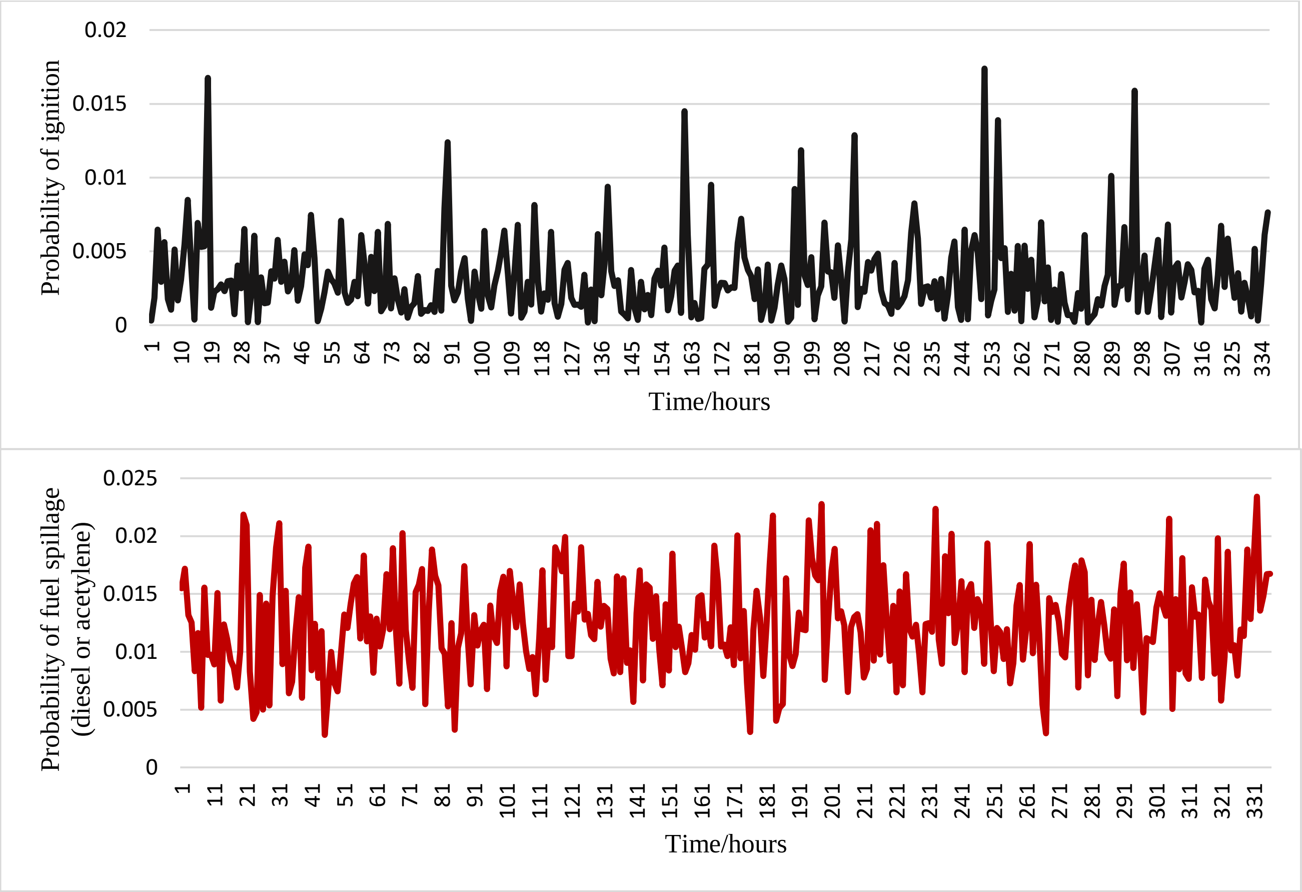


Figure 18. Probability of Ignition and Fuel Release

Table 8. Probability of Intermediate Events

	Generator spillage	**Compressor spillage**	**Diesel spillage**	**Acetylene spillage**	**Fuel spillage**	**Ignition**
minim	1.02E-04	7.76E-05	4.75E-04	8.15 E-04	2.36E-03	1.33E-04
maxim	9.70E-03	1.19E-02	1.36E-02	2.67E-02	3.40E-02	1.94E-02
mean	2.50E-03	2.94E-03	5.43E-03	7.18E-03	1.26E-02	3.31E-03
Coefficient of variation	7.33E-01	7.29E-01	5.49 E-01	6.05E-01	4.53E-01	8.92E-01

WANG (2015), estimated that the probability of the presence of an ignition source capable of causing fire and explosion ranges from 7E-02 to 4.75E-01. In an overview, WANG (2015), also estimated that the probability of fuel spillage ranges from 1.75E-02 to 3.25E-02. The results differ with those of the research because the analyzed components are significantly different.

4.4.Risk study of fire and explosion

Figure 19 shows the homogeneity study, the data are homogeneous, the model corresponds to the BETA 2 law and are modelled by 99.79%. Figure 20 shows the risk limits of fire and explosion occurrence. According to the Figure 21, the probability of fire and explosion ranges from 8.06E-07 to 2.73E-04.

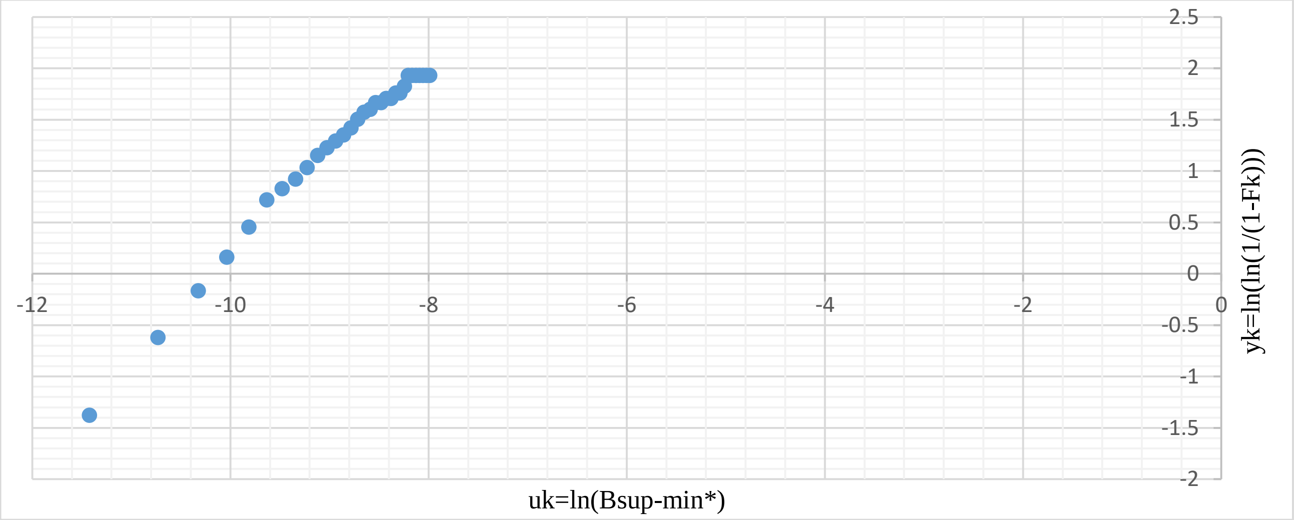


Figure 19. Study of the Homogeneity

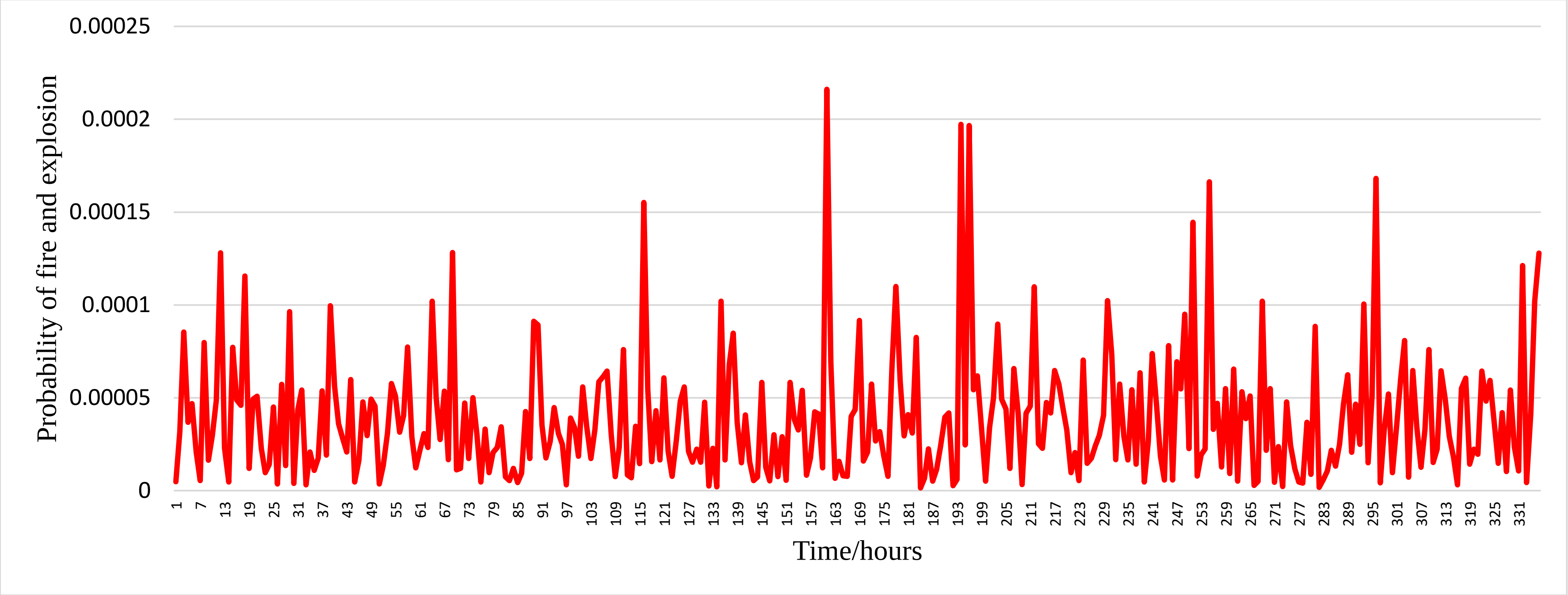


Figure 20. Probability of fire and explosion

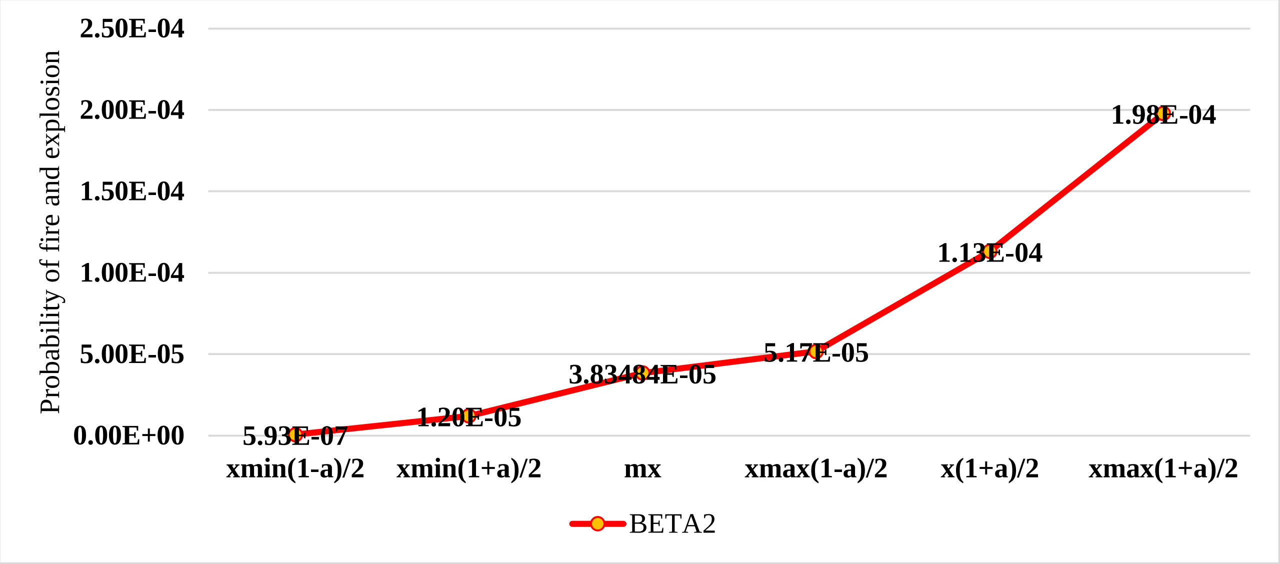


Figure 21. Study of Risk Limits

WANG (2015), estimated in his study that the probability of fire and explosion in an offshore installation ranges from 7.5E-03 to 2.25E-02. The result differs with those of the research because the analysed components are significantly different.

V. CONCLUSION AND RECOMMENDATIONS

5.1. CONCLUSION

Failure Modes, Effect and Analysis, Principal Component Analysis and Fault Tree analysis contributes on a very efficient way to the fire and explosion process modelling. Its helps to identify components with highest failure rates and their effects on the global system of the hot work operation. The results show that the class of critic failure modes contain A5 (surrounding heat), A6 (electric spark), A8 (seal leakage) and A9 (impeller leakage) and A10 (compressor tank failure). The probability of fire and explosion in the system ranges from 8.06E-07 to 2.73E-04. The results of this work are interesting to quantify probabilistically fire and explosion, and also for diagnostic purposes.

ISO 3834 is the international standard for quality requirements for fusion welding of metallic materials. ISO 9001 affirms that where necessary, special processes should be identified, and ISO 3834 is an excellent way to meet this requirement, because this practice can reduce or prevent financial losses due to operational failures that can be identified and controlled.

5.2.RECOMMENDATIONS

- **To Technip Energies**

To adopt rigorously the ISO 3834 standard during the hot work, which is the quality requirement for fusion welding of metallic materials.

To adopt the risk assessment methodology used in this research at the different levels of the operational system.

- **To future students**

To develop a mathematical modelling and simulation of heat dispersion due to fire and explosion.

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ANNEX 1: Interview Guide

UNIVERSIDADE
EDUARDO
MONDLANE

FACULTY OF ENGINEERING

DEPARTAMENT OF CHEMICAL ENGINEERING

MASTER DEGREE IN HEALTH, SAFETY AND ENVIRONMENTAL

Note: This document cannot be used for any other purposes other than for the preparation of the end-of-course assignment

<u>Interview Guide</u>

1. What is the main activity of this area?

2. What key processes are part of this activity that can influence the hot work chain?

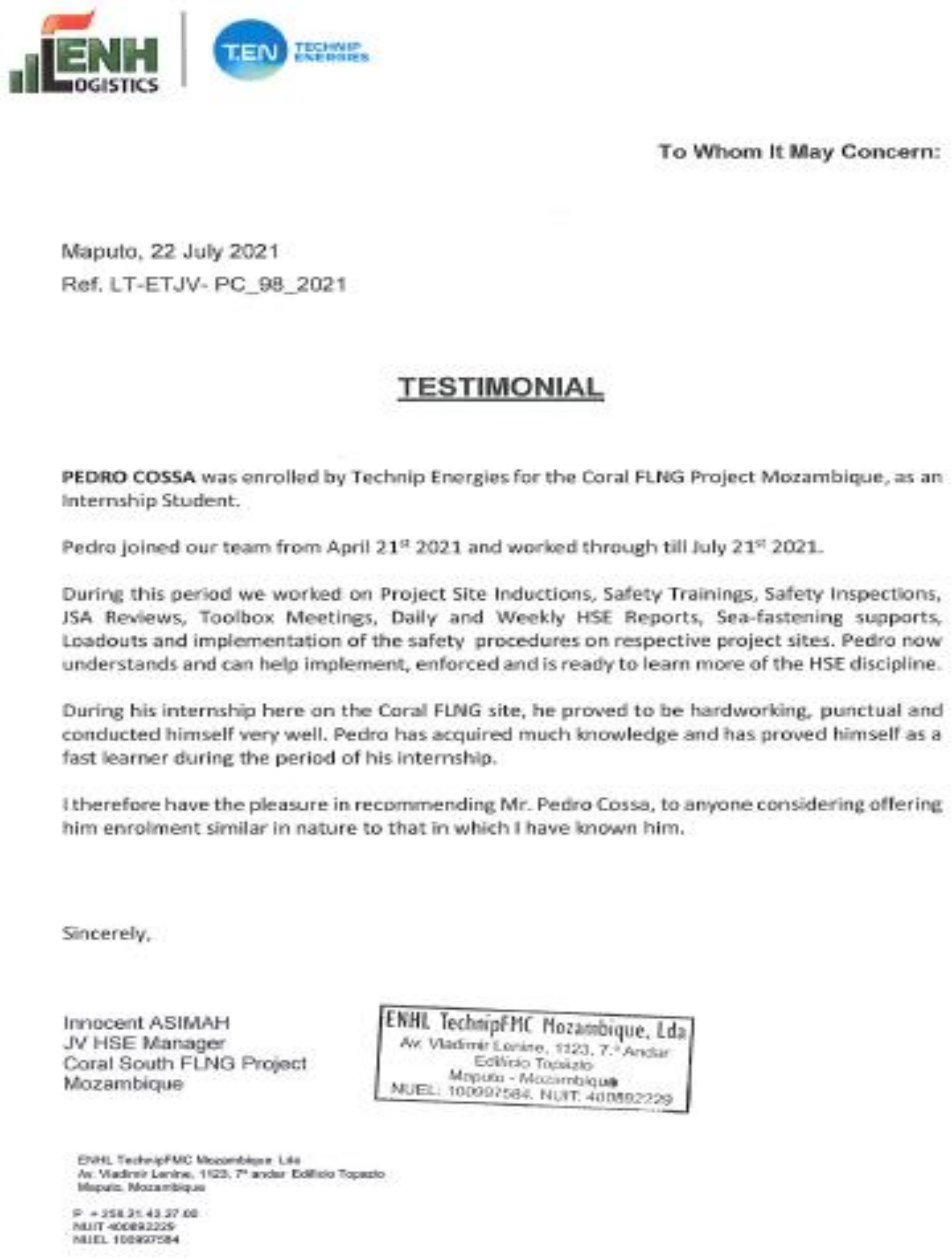
3. What hazards and risks are associated with these processes?

4. What is the likelihood of occurrence and impact if these risks materialise with respect to the operational chain?

5. Is there a procedure for managing these hazards and risks? What is it? And how does it work?

6. What measures are being implemented to mitigate the impact or eliminate the risks identified?

7. Do you have any ideas on how to improve the management of these risks and avoid disruption in the supply chain?



ENH LOGISTICS | T.EN TECHNIP ENERGIES

To Whom It May Concern:

Maputo, 22 July 2021
Ref. LT-ETJV- PC_98_2021

TESTIMONIAL

PEDRO COSSA was enrolled by Technip Energies for the Coral FLNG Project Mozambique, as an Internship Student.

Pedro joined our team from April 21st 2021 and worked through till July 21st 2021.

During this period we worked on Project Site Inductions, Safety Trainings, Safety Inspections, JSA Reviews, Toolbox Meetings, Daily and Weekly HSE Reports, Sea-fastening supports, Loadouts and implementation of the safety procedures on respective project sites. Pedro now understands and can help implement, enforced and is ready to learn more of the HSE discipline.

During his internship here on the Coral FLNG site, he proved to be hardworking, punctual and conducted himself very well. Pedro has acquired much knowledge and has proved himself as a fast learner during the period of his internship.

I therefore have the pleasure in recommending Mr. Pedro Cossa, to anyone considering offering him enrolment similar in nature to that in which I have known him.

Sincerely,

Innocent ASIMAH
JV HSE Manager
Coral South FLNG Project
Mozambique

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