UNIVERSIDADE EDUARDO MONDLANE

FACULTY OF ENGINEERING

Master in Health, Safety and Environment Engineering

RESILIENCE OF OPERATIONS IN THE REDUCTION DEPARTMENT AT THE MOZAMBIQUE ALUMINIUM MANUFACTURING PROCESS

A Dissertation Submitted to the Faculty of Engineering in Partial Fulfillment of the Requirements for the Degree of Master in Health, Safety and Environment Engineering

Student: David Gabriel Nhacassane

Maputo, November 2022

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Student: David Gabriel Nhacassane

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AUTHENTICITY STATEMENT

Statement of originality

I declare that this dissertation has never been presented for obtaining any degree or in another scope and that it constitutes the result of my individual work. This dissertation is presented in partial compliance with the requirements for obtaining the degree of master's in health safety, and environment engineering of Eduardo Mondlane University.

David Gabriel Nhacassane

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To my family for all support provided to me.

November 2022

David Gabriel Nhacassane

RESUMO

O conhecimento ou medição do nível de resiliência em sistemas de manucfatura é de extrema importância. Este exercício permite identificar os sectores vulneráveis do sistema fabril, que necessitam de melhorias para aumentar a segurança do processo produtivo. O resultado da medição de resiliência pode ser utilizado pelos gestores para avaliar, comparar e melhorar seus sistemas de produção, assim como apoiar de forma prática a tomada de decisão sobre custos de investimentos estratégicos para melhorar a resiliência de seus sistemas. Os atributos relacionados à resiliência incluem a gestão de energia, materiais, componentes, activos físicos e processos, transporte, cadeia de suprimentos, comunicações, logística, eficiência, produtividade, capacidade, segurança, confiabilidade do processo, qualidade, compatibilidade, sustentabilidade, trabalho e valores sociais. O principal objectivo do presente estudo foi avaliar o nível de resiliência das operações do Departamento de Redução da empresa Mozal Aluminium e, com base nos resultados, propor acções de melhoria através da utilização de métodos de gestão de risco. Os resultados do estudo mostraram que apesar das inúmeras avarias e paragens e algum grau de alta criticalidade em alguns modos de falha, o processo produtivo é resiliente, com um tempo de recuperação estimado em 16 horas, um nível de resiliência que é atribuído aos esforços da equipes de trabalho envolvidas nos diferentes turnos, para reparar as avarias. Esse cenário dá uma clara indicação de que a empresa deve introduzir acções no seu plano de manutenção do processo produtivo, com ênfase na manutenção preventiva e instalar dispositivos que de forma preditiva possam detectar as anomalias do processo produtivo. Essas acções não apenas aliviarão o estresse dos trabalhadores, mas também aumentarão a produtividade da empresa e a resiliência das suas operações.

Palavras-chave: Resiliência, confiabilidade, segurança, produção, manutenção.

ABSTRACT

The knowledge or measurement of the level of resilience in manufacturing systems is of utmost importance. This exercise makes it possible to identify the vulnerable parts of the manufacturing system, which need improvements to increase the safety of the production process. The result of the resilience measurement can be used by managers to evaluate, compare and improve their production systems, and can also practically support decision-making on strategic investment costs to improve the resilience of their systems. Resilience-related attributes include energy management, materials, components, physical assets and processes, transportation, supply chain, communications, logistics, efficiency, productivity, capacity, safety, process reliability, quality, compatibility, sustainability, work and social values. The main objective of the present study was to assess the level of resilience of operations in the Reduction department at Mozal Aluminium Company and, based on the results, to propose improvement actions through the use of risk management methods. The results of the study showed that despite the numerous breakdowns and downtime and some degree of high criticality in some failure modes, the production process is resilient, with an estimated recovery time of 16 hours, a level of resilience that is attributed to efforts of the work teams involved in the different shifts to fix breakdowns and eliminate late work. This scenario gives a clear indication that the company must introduce actions in its production process maintenance plan, with emphasis on preventive maintenance and installing early warnings in PTAs. These actions will not only relieve workers' stress but will also increase the company's productivity and resilience of operations.

Keywords: Resilience, reliability, safety, production, maintenance.

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LIST OF ABREVIATIONS AND ACRONYMS

AP	-	Systems applications and products
BN	-	Bayesian network
ETA	-	Event tree analysis
ETA	-	Event tree analysis
FA	-	Functional analysis
FMECA	-	Failure Modes, Effects and Criticality Analysis
FTA	-	Failure tree analysis
HROs	-	High-reliability organizations
HSE	-	Health, safety and environment
MARL	-	Monitoring, anticipation, response, and learning
MMS	-	Central maintenance system
MOZAL	-	Mozambique Aluminium
MTTF	-	Mean time to failure
PCA	-	Principal component analysis
POC	-	Penalty of change
PTA	-	Pot tending assembly
PTAs	-	Pot tending assemblies
PTAs1,2,3	-	PTA components 1,2,3
RE	-	Resilience engineering
REA	-	Resilience Engineering Association
RPTA	-	Reliability of PTA system
RPTAs	-	Reliability of PTA components
SC	-	Supply chain
STAMP	-	Systems-Theoretic Accident Modeling and Processes

CHAPTER 1 - INTRODUCTION

The aluminium industry is of a vital importance to the world economy. Aluminium's special qualities have enabled advances in technologies coupled with energy and cost savings. Aircraft capabilities have been greatly enhanced and increases in size and capacity are made possible by advances in aluminium technology. The aluminium industry is therefore a pivotal one for ecological sustainability and strategic for technological development (Kvande, 2014).

In a globalized world, characterized by a competitive and strictly interconnected economy, manufacturing systems have the challenge of being always equipped with adaptive capacity and prepared to deal with unexpected events, respond to disruptions in the flow of goods and also have the ability to recover from these events, maintaining the continuity of operations at a desired level of connectivity with the market. Resilience is one of the main characteristics that manufacturing systems must have, as it offers companies the ability to withstand difficult situations and be able to accommodate disruptions without incurring significant additional costs (Alexopoulos et al., 2021). Resilience is a quantitative measure of performance that represents the ability of a system to survive unexpected disruptive events or an undesired situation and how quickly it recovers after the disruptive event occurs.

The quantitative measurement of resilience is extremely important because, in addition to being able to identify, for example, vulnerable parts of the manufacturing system, which need improvement to increase the safety of the process, it can be used by managers to evaluate, compare and improve the performance of their production systems. Quantitative measurement of resilience can also practically support decision-making on strategic investment costs to improve the resilience of their systems (Alexopoulos et al., 2021). Other benefits of measuring resilience include better understanding and the ability to compare different systems and configurations under different environmental, organizational, social, and economic conditions. A list of attributes related to resilience may include energy management, materials, components, physical assets and processes, transportation, supply chain, communications, logistics, efficiency, productivity, capacity, safety, process reliability, quality, compatibility, sustainability, workforce and social values (Kusiak, 2019).

Given the significant negative impact that disruptive events have on manufacturing systems, studies around resilience issues have been gaining increasing relevance in the productive sector. However, at the national level, research work on resilience estimation in manufacturing systems has been very scarce, if any, they are still not officially documented. The present work intends to bring this approach to a practical way of trying to assess the resilience of the Mozambique Aluminium (Mozal) company's manufacturing process. For the present study the emphasis was given to the operations of the reduction department.

1.2.Motivation

Preventing breakdowns in machinery or equipment in a production process is a fundamental characteristic of any industrial activity. However, to reduce the chance of occurrence of these malfunctions, which often generate losses of time, resources, material damage or lead to the reduction of workers' working life or losses of life, companies must make their production systems as safe as possible. According to Hollnagel (2010), making a resilient system by adding and developing specific resilience engineering skills makes the system consequently become safer. For this, it is necessary to establish a matrix of competencies that include the pillars of resilience engineering. Given the significant negative impact that disruptive events have on manufacturing systems, studies around resilience issues have been gaining increasing relevance in the productive sector. At the national level, research works on this matter are scarce, if they exist, then they are not yet officially documented. Faced with this reality, the candidate saw an opportunity to bring this approach to a practical and concrete way, and applying the tools acquired in the master's course in Health, Safety and Environment, trying to quantify the resilience of operations in the reduction department at the Mozal company. The operations in the reduction section of Mozal, have been suffering constant interruptions due to constant breakdowns in the main equipment of the process, a situation that somehow compromises the normal course of production activities. With the quantification of the resilience level in the operations, are expected concrete results, enhancing the improvement of the adaptive capacity of the system to resist unexpected events and the ability to recover from events that have already occurred.

1.3. Problem statement

The knowledge or measurement of the level of resilience in manufacturing systems is of utmost importance. This exercise makes it possible to identify the vulnerable parts of the manufacturing system, which need improvements to increase the safety of the production process. The result of the resilience measurement can be used by managers to evaluate, compare and improve their production systems, and can also practically support decision-making on strategic investment costs to improve the resilience of their systems. Resilience-related attributes include energy management, materials, components, physical assets and processes, transportation, supply chain, communications, logistics, efficiency, productivity, capacity, safety, process reliability, quality, compatibility, sustainability, work and social values.

Given the relevance around the issue of “resilience”, several studies have been carried out around the world using different approaches or methods of measurement or quantification. However, at the national level, research works on this matter are scarce, if they exist, then they are not yet officially documented. The present work intends to bring this approach to a practical way of trying to quantify the resilience of operations in the reduction department at the Mozal Company.

Mozal is an aluminium smelting company that has been operating in Mozambique since 2000. Like any other aluminium production industry, the process of obtaining aluminium at Mozal occurs by reducing calcined alumina in electrolytic vats at high temperatures, in a process commonly known as Hall-Heroult. Meanwhile, operations in the company's reduction section have suffered constant interruptions due to constant breakdowns in the main process equipment, a situation that somehow compromises the normal course of production activities. The present work seeks to apply the tools acquired in the Master's course in Health, Safety and Environment to verify if the structure of the company's reduction department meets the requirements of a resilient system and later to make comments around this structure, highlighting positive points and opportunities for improvements.

1.4. Objectives

The main objective of the study is to assess the level of resilience of operations in the Reduction Department at the Mozal manufacturing process and based on the results, to propose improvement actions through the use of risk management methods.

1.4.1. Specific objectives

(i) Assess the current level of resilience of operations in the Reduction Department of Mozal's production process;

(ii) Calculate operations resilience;

(iii) Perform qualitative and quantitative analysis; and

(iv) Propose improvement actions.

1.5. Methodology

Five main phases were followed in the present research work namely:

(1) Continued relevant literature review for the proposed study area, including consultation of internal company documents;

(2) Data collection and processing;

(3) Data analysis;

(4) Analysis and discussion the obtained results; and

(5) Elaboration of the dissertation.

1.6. Dissertation structure

In total, the dissertation comprises five chapters and references. An introduction to the study, motivation, problem statement, research objectives and methodology are given in Chapter 1. Chapter 2 provides an overview on the resilience engineering history, resilience concepts, methodologies to measure resilience, relation between resilience and safety. In chapter 3 detailed description in terms of resilience calculation and application of proposed methods to suggest enhancement of resilience are given. The results and discussions of the study are presented in Chapter 4. The key findings of the study, including conclusions recommendations are given in the Chapter 5, and the main references consulted for the study are listed in the item of "References".

CHAPTER 2 - LITERATURE REVIEW

2.1. History and use of the term Resilience in different disciplines

According to Doorn (2020) much of the literature on resilience refers to the work of the ecologist Holling, who introduced the term in the context of ecosystems. The first use in an engineering context can be found at the beginning of the nineteenth century, where resilience was used to describe the property of certain types of wood that could accommodate sudden and severe loads without breaking. In the mid nineteenth century, the naval architect of the British Admiralty, Robert Mallet, used the phrase “modulus of resilience” as a measure for assessing the ability of materials to withstand severe conditions in warship design. Thus, although not the source of the first use of the term, Holling’s paper is probably one of the first in which an attempt is made to provide a more precise description of “resilience”.

Drawing on examples from ecology, Holling distinguished resilience from stability, defining the latter as “the ability of a system to return to its equilibrium state after a temporary disturbance”. He described resilience, however, as “the persistence of systems and their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables”. Hence, resilience does not require a system to return to an equilibrium state. Resilience, according to Holling, is primarily about being able to absorb and accommodate unexpected future events (Doorn, 2020).

After its introduction in ecology in the 1960s and 1970s, the term “resilience” became popular in other domains as well, entering the field of safety management around 2000, as well as other fields such as psychology, disaster management, and even business. With the use of the same term in different domains, different definitions and interpretations emerged (Doorn, 2017). In the last decade, several studies have been published that refer to various meanings and definitions of resilience.

According to Pasman et al. (2020) it is known that resilience’s root is mechanical or according to a web definition by Oxford Dictionaries: “the ability of a substance or object to spring back into shape; elasticity”. As a metaphor, psychologists have already used it for 50 years in connection with the ability of an individual to recover from mental stress and trauma or trying to enhance an individual’s resilience. Via culture and strife from high-reliability organizations (HROs) in the 1990s, resilience became a property of organizations. In 2004, psychologist and risk assessor

Erik Hollnagel with David Woods and Nancy Leveson organized the first conference on resilience engineering. This focused on organizational resilience and the ability to maintain safety. Four cornerstones of resilience were identified: Monitoring, anticipation, response, and learning (MARL).

2.2. Resilience concepts

The concepts of resilience have been proposed by various actors since 2006 to 2021 where , Hollnagel et al (2006) define also Resilience as ability of systems to anticipate and adapt to the potential for surprise and failure or Resilience is often defined in terms of the ability to continue operations or recover a stable state after a major mishap or event and defines Resilience as the ability of an organization (system) to keep, or recover quickly to, a stable state, allowing it to continue operations during and after a major mishap or in the presence of continuous significant stresses.

In 2009 Storseth and co-workers defined resilience as the system capability to prevent or adapt to changing conditions in order to preserve its control over a system property. According to these authors, the concepts of resilience and Resilience engineering (RE) can be distinguished by thinking of (i) 'resilience' as a set of theories or ideas, all concerning coping abilities of socio technical systems; not as some static property that the organization possesses but more along the lines of what an organization does and (ii) 'Resilience Engineering' as a specific approach working to manage risk in a proactive manner. Resilience Engineering is based on findings concerning failures in complex systems that involve both organizational level risk factors and factors that may affect human performance.

Hollnagel (2010) define resilience as ability to deal with risks and threats, the ability of the system adjusts its functioning prior to, during, or following changes or disturbances so that it can sustain required operations under both expected and unexpected conditions. Moritz Schattka (2016) defines resilience as the ability to continue operations or recover a stable state after a major mishap or event. This definition focuses on the reactive nature of resilience and the ability to recover after an upset. Han (2016) defines Resilience as a property that allows the system to be persistent against the changes. Ares Enrique & Ferreira (2012) define resilience as the ability to restore performance after sustaining serious damage by a usually unexpected threat. Resilience is a performance measure representing the system ability to survive disruptive events, and the rapidity in restoring system capacity after the disruptive event has occurred (Caputo et al., 2019). According to Doorn (2020), resilience is the ability of a system to return to its equilibrium state after a temporary disturbance. Resilience can be perceived as a system's ability to adjust to a change and recover from an undesired state to a desired one (Alexopoulos et al, 2021). The concepts above suggest some qualities or abilities that a resilient system should have. Specifically, it is suggested that a resilient system has the abilities to: persist return to its equilibrium, Recover, continue operations, restore performance, deal with risk, adjust, prevent.

According to Pawar et al. (2021) After reviewing the studies related to industrial systems it is clear that the research in resilience of process industries is heavily focused on analyzing the effects of socio-technical factors. This is because of the inherent nature of the concept of resilience which deals with human factors. While addressing the resilience of process industries, it is particularly important to analyze the factors affecting resilience quantitatively as well as qualitatively .

According to Pawar et al. (2021) there is no universally accepted definition because the term "resilience" has been defined by researchers in ways that are specific and suitable for their research fields. Therefore, there are multiple definitions of resilience which are available in the literature.

2.3. Resilience engineering: A new paradigm of safety management

The origin of the resilience engineering paradigm is often linked to the first symposium of the Resilience Engineering Association (REA), which was held in 2004 and which has since been organized once every two to three years (Patriarca et al., 2018). The discussions and after thoughts of the first four symposia were documented in a series of volumes dedicated to both theoretical and conceptual work as well as more practical applications. Especially in the early years of REA's existence, some important conceptual work was done to clarify the term "resilience engineering" and its relation to more traditional approaches to safety management. Erik Hollnagel, one of REA's co-founders and a leading scholar in resilience engineering, describes it as part of a Safety-II paradigm, while Safety-I is used to refer to traditional approaches to safety management (Doorn, 2020). Although Safety-I and Safety-II should not be seen as entailing incompatible or conflicting views, for the sake of clarity it is worth discussing the main differences. The following discussion is largely based on Hollnagel's deconstruction of the two paradigms in terms of their phenomenology, etiology, and ontology. Resilience engineering is a paradigm for safety management that focuses on how to help people cope with complexity under pressure to achieve success (Hollnagel et al., 2006).

2.4. Methods to measure the Resilience

Resilience Engineering represents a new way of thinking about safety. Whereas established risk management approaches are based on hindsight and emphasize error tabulation and calculation of failure probabilities, Resilience Engineering looks for ways to enhance the ability of organisations to create processes that are robust yet flexible, to monitor and revise risk models, and to use resources proactively in the face of disruptions or ongoing production and economic pressures (Dekker et al., 2008).

Quantitative measurement of resilience can provide various benefits, such as better understanding and the ability to compare different systems and configurations under different environmental, organisational, social, and economic conditions. In addition, it can identify vulnerable parts that need improvement for increasing resilience and enhancing transparency in the underlying infrastructure. The resilience measure can be used by managers to assess, compare and improve their production systems, and decide on strategic investment costs to improve systems' resilience. It can be applied for several disruption scenarios or variations of the same disruption scenario with different disruption characteristics, such as duration, recovery time and impact on the production system (Alexopoulos et al., 2021).

Han, et al. (2016) proposes a new concept called resilience of algorithm in the context of operation management of a system. Han, et al .2016 proposes a new concept called resilience of algorithm in the context of operation management of a system. Resilience is a behavioral property of the system and it refers to the persistence of the system performance when the system is subject to damages. Operation management of a system can be modeled as a mathematical problem. Algorithms are to generate a solution to the mathematical problem. When a system is subject to damage, the corresponding mathematical problem is changed. The resilience of a system thus reduces to the issue of how and whether the existing algorithm can still generate a solution to the changed problem. Han, et al. (2016) further proposes a measure of the resilience of algorithm and takes a supply chain schedule algorithm as an example to validate the proposed measure, the goal is to develop a quantitantive measure for the resilience of algorithm, where the definition of resilience is a behavioral property of the system and it refers to the persistence of the system performance when the system is subject to damages (Han et al., 2016). Also In 2016 Hosseini and collaborates, implemented Bayesian Network (BN) approaches to quantify the resilience of the Supply Chain (SC).

Alexopoulos et al. (2021) provide a measure for resilience quantification in manufacturing systems, and its validation in an industrially-relevant scenario. Two individual systems are selected to demonstrate the approach: (1) a 3D printing farm; and (2) an injection moulding plant. The first system uses Additive Manufacturing technology to build products, whereas the second one uses Injection Moulding techniques. Since production technologies can produce identical products, their selection enables comparison between them on various occasions, favouring the one or the other system, making it feasible to validate and assess the sensitivity of the proposed measure, the Penalty of Change (POC) measure is used in Alexopoulos et al., (2021) study. POC is a generic measure that can be applied in different set-ups and manufacturing domains. It combines both technological and economical terms and does not require large and complex amounts of data for calculations. It is easy to apply to realistic manufacturing situations by practitioners and be interpreted by the persons in charge. The calculation of the POC measure is dependent on the probabilities estimation, which is prone to errors. Thus, its accuracy can be high and low (Alexopoulos et al., 2021).

The calculation of the POC is based on two variables: (1) the cost of the potential change; and (2) the probability of change, where a 'change' is meant to be a transition from a current 'state' of a manufacturing system to another one. Cost and probability of change can be considered as a function of the discrete variable *X*, which represents the potential changes. The *i*-th value of *X* is designated as *X*. Then, the POC can be calculated by the below formula as shown in equation 1 (Alexopoulos et al, 2021)

Equation 1:Calculation of POC

$$POC = \Sigma i = 1DPn(Xi)Pr(Xi) \quad (1)$$

Where:

D is the number of potential changes,

X is the *i*-th potential change,

Pn(*X*) is the penalty (cost) of the *i*-th potential change and, *Pr*(*X*) is the probability of the *i*-th potential change to occur.

A manufacturing system can be considered a continuous system. In such a case, there is an infinite number of potential transitions and the variable *X*, representing the change scenarios, is then continuous. The cost of a potential change is represented by a continuous distribution *Pn*(*X*), while at the same time, the probability of change is also designated by a continuous probability distribution *Pr*(*X*). The product *Pn*(*X*)*Pr*(*X*) is a distribution of the 'normalised' distribution cost, with its integral being the expected value of cost, which provides a measure of the system's resilience. Then, the POC calculation formula is transformed as shown in equation 2 (Alexopoulos et al., 2021):

Equation 2: POC calculation 2

$$POC = \int X1X2Pn(X)Pr(X)Dx \tag{2}$$

where:

*X1*is the lowest value of the potential change *X*,

*X2*is the highest value of the potential change *X*,

Pn(*X*) is the cost distribution and

Pr(*X*) yields the probability distribution of the potential change.

The POC calculation may be thought of as a single attribute decision-making under uncertainty, including potential change scenarios, the probabilities and a typical penalty cost of each individual scenario. POC is proposed as a generic measure, since it combines technological and economic terms. It does not require large and complex amounts of data for calculations. In contrast with the majority of literature approaches, it is relatively easy to be applied to realistic manufacturing situations and to be interpreted by the management follows (Alexopoulos et al., 2021).

Resilience is a concept, amenable to quantitative measurement, combining both the robustness of a system, the ability to survive disruptive unexpected events, and the capability of rapidly restoring its capacity after the disruptive event has occurred (Caputo et al., 2019). Caputo et al. (2019) presented a quantitative method to compute plant resilience, the method is developed with reference to manufacturing plants. The method is presented in a deterministic context but it is easily extended to a probabilistic setting. It allows a direct assessment of the initial capacity loss following a disruptive event, as well as the time-dependent capacity recovery path and the connected economic loss due to capacity reconstruction and business interruption. The model can act as a decision support tools for facility designers and emergency managers. Caputo et al. (2019) assume that the impact of a disruptive event on plant capacity, in terms of flow rate of the physical production output, may be generally represented by the generic time trend shown in Figure 1, where the nominal capacity $C(t_0)$ is reduced to the residual value $C(t_d)$, including the case $C(t_d) = 0$, at time td following the abrupt occurrence at time t_0 of the disruptive event. The disruption can be any event determining a partial or total reduction of plant output owing to damage of one or more equipment or building (i.e., after a natural disaster), or the interruption of an external material flow feeding the plant (i.e., delivery interruption from a 1st tier supplier). In most cases time interval (t_d-t_0) can be considered negligible (Caputo et al. 2019). Following a latency period $(t_i - t_d)$ to allow for damage recognition and planning of required actions, starting from time t_i, capacity is gradually recovered and becomes fully restored at time t_r. The time trend of capacity recovery needs not to be linear, as shown in the Figure 1, as it depends on the plant configuration, actual equipment damage and the time-phased sequence of restoration activities (Caputo et al.,2019). In the special case of immediate start of a linear recovery, then the area above the capacity curve becomes triangular, thus justifying the reference to a so called "resilience triangle"; The scope of the method is to determine the actual C(t) function as well as the recovery interval TR = $(tr – t_0)$ in order to allow resilience computation.

Equation 3: Resilience calculation

$$Resilience = \frac{1}{t_r - t_0}\int_{t_0}^{t_r} C(t)dt \tag{3}$$

The model includes the following sequential steps.

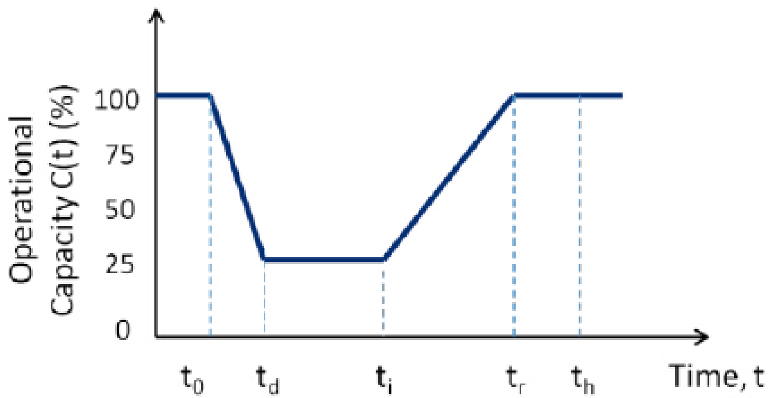

Figure 1: Diagram of capacity vs time (Adapted from Caputo et al., 2019).

Pasman at al. (2020) proposed an algorithm depicted in Figure 2 to evaluate process resilience in index form using the principles and contributing factors with multi-factor approach and in Figure 3 demostrate the principles and contributing factors of process resilience.

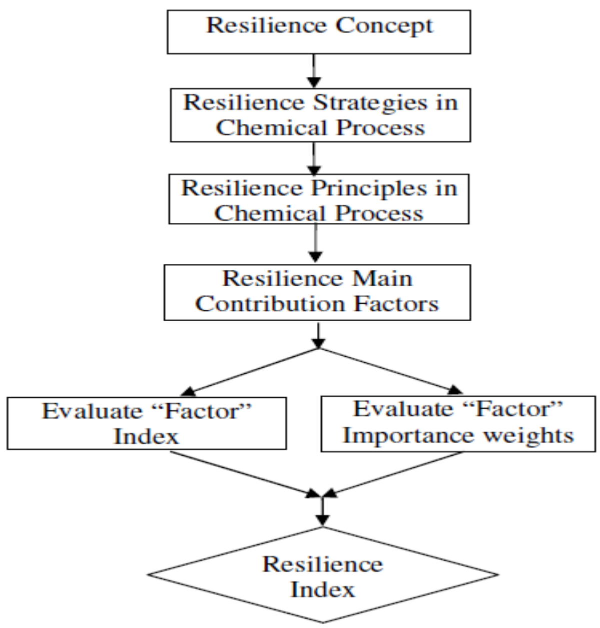

Figure 2: Process resilience evaluation algorithm (adapted from Pasman at al., 2020).

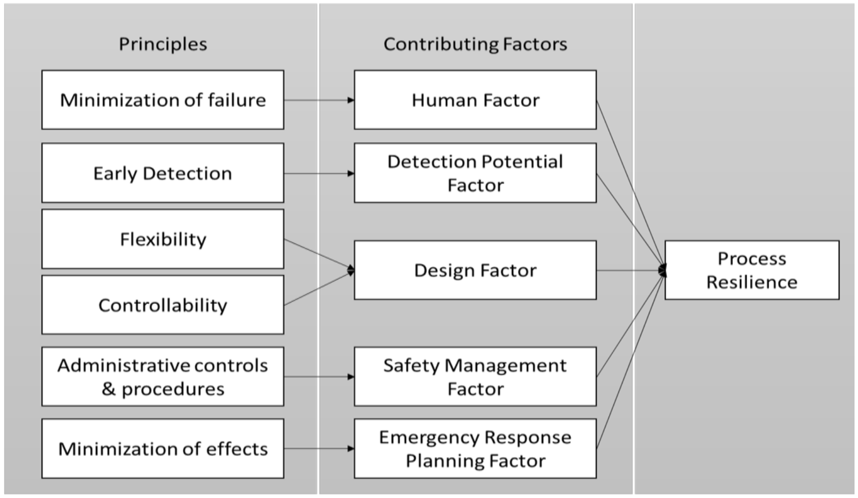

Figure 3: Principles and contributing factors of process resilience (adapted from Pasman at al., 2020).

According to Pasman at al. (2020) proposed as a further refinement PRAF, the novel process resilience analysis framework is presented in Figure 4

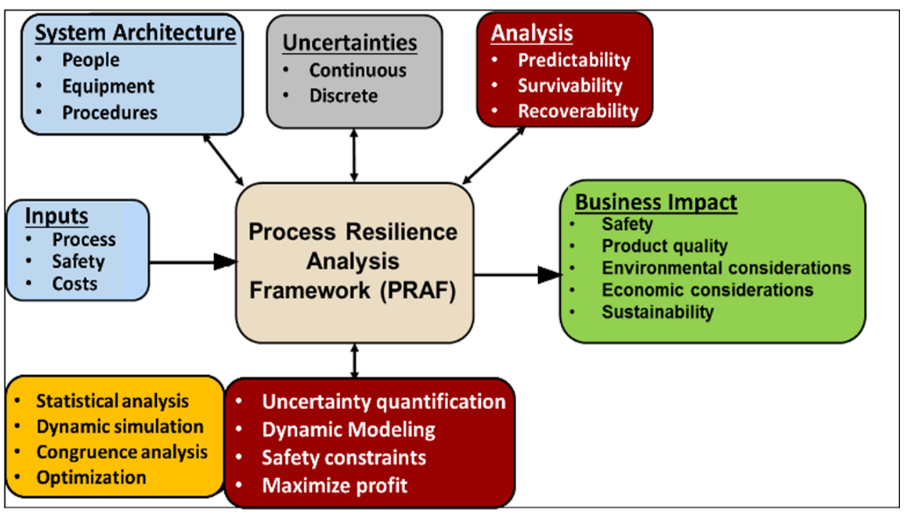

Figure 4: The process resilience analysis framework (adapted from Pasman et al., 2020).

Pasman et al. (2020) proposed a way that established an accurate and integrated method to predict process upset situations by applying the resilience approach. This way enables a rather comprehensive upset risk probability determination as a function of process conditions taking account of historical Sustainability data, actual organizational effectiveness related indicators (social metrics) and equipment failures, including uncertainty ranges in the various inputs. This can serve to optimize profitability under the constraint of safe process operations by avoiding hazardous zones. In simple form Figure 5 depicts the analysis scheme. Scenario analysis and Bayesian analysis are performed a detailed process simulation providing insight in the process dynamics, and a global sensitivity analysis of inputs versus outputs, done before the Bayesian uncertainty analysis and thereafter investigation of flexibility within acceptable bounds and economic optimization.

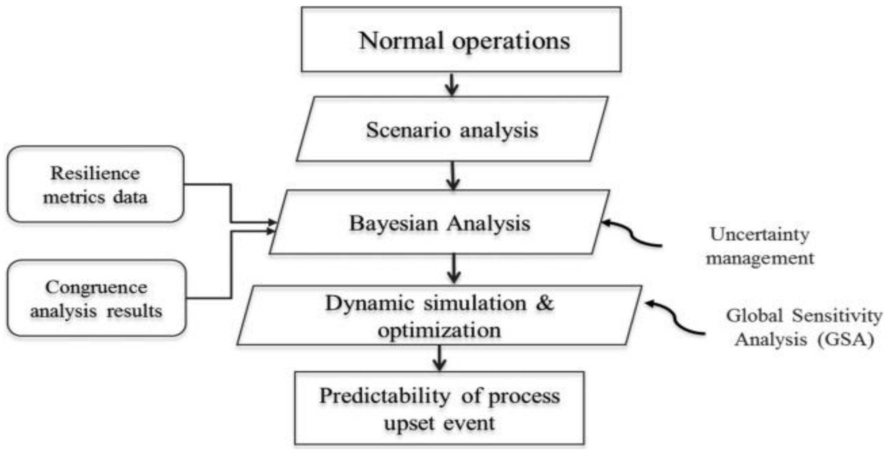

Figure 5: Flow scheme of the resilience analysis resulting in a process upset prediction (adapted from Pasman et al., 2020).

Schattka et al. (2016) presents a method to assess the performance of a production system in face of disruptions and to identify the overall effective level of resilience for a production system. A framework is introduced, consisting of a stochastic simulation and an optimisation method. Out of a structured description of any arbitrary production line the framework generates a detailed simulation of it.This simulation represents the production line in all relevant properties and incorporates disruptions as stochastic influences. A genetic algorithm was selected to perform the optimisation in this work. The algorithm evolves the most effective configuration of the line through repeated, parallel cycles of simulation. This particularly, but not exclusively, concerns the optimal size and location of buffers.

Pasman at al. (2020) analyzes resilience of process plants as there are oil and gas refining, chemical manufacturing, power-producing plants, and many more. Besides the conceptual details, cases are presented that show how human and technical factors, combined in a sociotechnical system, can lead to a broader plant safety insight enabling more effective risk control and increased resilience. The figure 6 represents performance overtime of two identical process plants, in which case 2 has been better prepared for unexpectedly hitting threat. Damage is less deep and recovery is faster (Pasman at al., 2020).

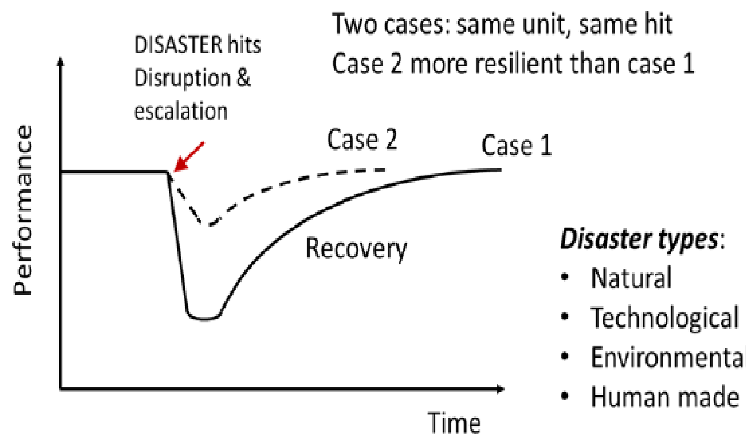

Figure 6: The concept of resilience applied to a process plant (Adapted from Pasman et al., 2020).

Pasman et al. (2020) explain that according to Figure 6, it is clear that when management receives a warning, when it is prepared and responding adequately, damage at a given threat may be less deep and recovery more rapid (Case 2). In such case, the organization is considered more resilient. To realize such performance of Case 2 requires much of top-management, leadership, and the rest of the organization and the technology. Resilience has social and technical aspects; good resilience requires the right attitude of the individuals involved, the organizationas a whole, and it sets requirements for the plant installations. Treating resilience will include implementation of these aspects.

2.5. Mechanisms to enhance resilience

Pillay (2016) suggested that resilience capability played a role in facilitating adaptation which is crucial in resilience engineering process, four of these suggested to represent the basic foundation of resilience engineering (RE), have been identified, including anticipation, responding, learning and monitoring as described bellow:

- **Anticipation** - is the ability to adress the potencial, and is chareterized by knowing what to expect (in terms of threat and opporttunities) in the future (pontetial changes, desruptions, pressure) and the consequences of these;
- **Responding** - is the ability to adress what is right and is chareterized by knowning what to do (when faced with regular, irregular or unexampled threats) either trough prepared set of responses or by adjusting normal functioning;

- **Learnig -** is the ability to adrress the factual, and is charaterized by learning the right lessons by the right experience (both success and failure); and
- **Monitoring -** is the ability to adress the critical, is charaterized by knowing what to look for both in the environment and in the system.

According to Doorn (2020), the four abilities discussed describe a resilient system as one that is able to respond to the actual, to monitor the critical, to anticipate the potential, and to learn from the factual.

The focus on the issues arising from each of the four corner stones demonstrate how it is possibleto think about resilience engineering in a practical manner starting from the level of the system as a whole this soon leads to the development of operational details and specific steps to be taken on a concrete level (Dekker et al., 2008).

According to Doorn (2020), depending on the complexity of the system that is the focus of resilience engineering, has more to add to traditional approaches to safety management, however, some measures to improve the four abilities in the Resilience paradigm may be quite similar to those in traditional safety management.

2.6. Resilience and Safety

Resilience Engineering represents a new way of thinking about safety (Dekker et al., 2008). To ensure safety, the system or organisation must be resilient in terms of avoiding failures and losses, as well as responding appropriately after the fact (Hollnagel et al. 2006).

Hollnagel et al. (2006) determined how to design resilient systems that respond to the pressures and influences causing the drift to states of higher risk or, if that is not possible, to design continuous risk management systems to detect the drift and assist in formulating appropriate responses before the loss event occurs. The approach rests on modeling and analyzing socio-technical systems and using the information gained in designing the sociotechnical system, in evaluating both planned responses to events and suggested organizational policies to prevent adverse organizational drift, and in defining appropriate metrics to detect changes in risk (Hollnagel et al., 2006). To be useful, such modeling and analysis must be able to handle complex, tightly coupled systems with distributed human and automated control, advanced technology and software-intensive systems, and the organizational and social aspects of systems, to do this, was used a new model of accident causation, the so-called “Systems-Theoretic

Accident Modeling and Processes (STAMP)", based on system theory. STAMP includes nonlinear, indirect, and feedback relationships and can better handle the levels of complexity and technological innovation in today's systems than traditional causality and accident models. STAMP can be used as a foundation for new and improved approaches to accident investigation and analysis, hazard analysis and accident prevention, risk assessment and risk management, and for devising risk metrics and performance monitoring (Hollnagel et al., 2006) .

2.7. Methods used to measure and enhance resilience in this study

From the litarature research the method found suitable to calculate resilience for reduction operations is the method used by Caputo et al. (2019), this method allows a direct assessment of the initial capacity loss following a disruptive event, as well as the time-dependent capacity recovery. According to Pawar et al. (2021), for applications of mathematical modeling in resilience engineering, it was observed that exploring mathematical assessment frameworks has been the major focus for the past six years and it can be observed that mathematical modeling has played a significant role in the research on the resilience engineering applications, however to enhance Resilience in this study methematical methods were used to respond the purpose of some of the four corner stones of resilience wich are: Monitoring, anticipation, response and learning (MARL).

According to Doorn (2020), some measures to improve the four abilities in the Resilience paradigm may be quite similar to those in traditional safety management. However based on Doorn statement in this project different methods were used to analyse and sugest improvement in reduction department resilience such methods are:

- Principal components analysis;
- Functional analysis;
- Fault tree analysis;
- Event tree analysis;
- Failure Modes Effects And Criticality Analysis (FMECA); and
- Reliability.

2.7.1. Principal components analysis (PCA)

Principal Component Analysis (PCA) is the general name for a technique which uses sophisticated underlying mathematical principles to transform a number of possibly correlated variables into a smaller number of variables called principal components. The origins of PCA lie in multivariate data analysis, however, it has a wide range of other applications. In general terms, PCA uses a vector space transform to reduce the dimensionality of large data sets. Using mathematical projection, the original data set, which may have involved many variables, can often be interpreted in just a few variables (the principal components). It is therefore often the case that an examination of the reduced dimension data set will allow the the user to spot trends, patterns and outliers in the data, far more easily than would have been possible without performing the principal component analysis (Richardson, 2009).

2.7.2. Functional analysis

Functional Analysis is a fundamental tool of the design process to explore new concepts and define their architectures. When systems engineers design new products, they perform functional analysis to define the new product's functional requirements, to map its functions to physical components, to guarantee that all necessary components are listed and that no unnecessary components are requested and to understand the relationships between the new product's components (Viola et al., 2012). Function Analysis is also a primary tool for quality function deployment, requirements engineering, and value engineering. The information obtained during the functional analysis is used to identify the product structure which reveals the technical parameters needed for the quality function deployment process (Ilie et al., 2011).

On the basis of the mission objectives/top level system requirements the functional tree has to be developed as first step of Functional Analysis. Once the basic functions have been identified and the functional tree has therefore been completed, the functions/components matrix can be built and the basic components of the product tree can be individuated. Once the basic components have been determined, both the product tree and the connection matrix can be completed (Viola et al., 2012).

2.7.3. Fault tree analysis

Fault tree analysis (FTA) is a top-down approach to failure analysis, starting with a potential undesirable event (accident) called a TOP event, and then determining all the ways it can happen. The analysis proceeds by determining how the TOP event can be caused by individual or combined lower level failures or events. The causes of the TOP event are "connected" through logic gates (Rausand, 2005).

FTA was first used by Bell Telephone Laboratories in connection with the safety analysis of the Minuteman missile launch control system in 1962. The technique was late on improved by Boeing Company and extensively used and extended during the Reactor safety study (Rausand, 2005). It comprises two main steps namely (i) construction of the fault tree and (ii) quantitative analysis of the fault tree.

According to Rausand (2005), to define the TOP event in a clear and unambiguous way it should always answer: What-what happend, Where-place where the event happened, and When-when it happened.The immediate, necessary, and sufficient events and conditions causing the TOP event are connected via logic gates: AND or OR gate, see figure 7.

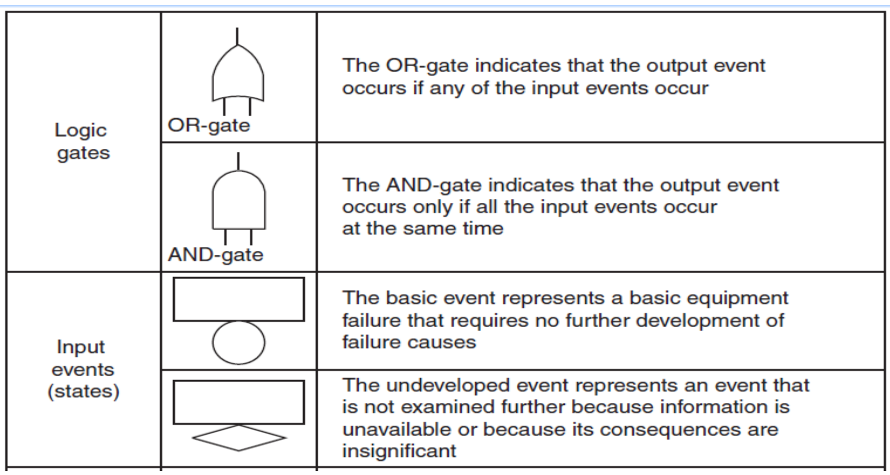

Figure 7: Fault tree symbols (adapted from Rausand, 2004).

2.7.4. Event tree Analysis

An event tree analysis (ETA) is an inductive procedure that shows all possible outcomes resulting from an accidental (initiating) event, taking into account whether installed safety barriers are functioning or not, and additional events and factors (Rausand, 2004).

By studying all relevant accidental events (that have been identified by a preliminary hazard analysis, a HAZOP, or some other technique), the ETA can be used to identify all potential accident scenarios and sequences in a complex system (Rausand, 2004).

2.7.4.1. Event tree construction

The event tree construction obey below steps (Rausand, 2004) :

1. Identify the unwanted event that may have negative consequences;
2. Indicate the probable senarios that if followed or not followed may lead to consequences
3. Construction of the event tree;
4. Describe the potential events and barriers sequences;
5. Determine the probabilities of the branches in the event tree;
6. Calculate the probabilities for the identified consequences; and
7. Compile and present the results from the analysis.

Consider the generic example shown in Figure 8:

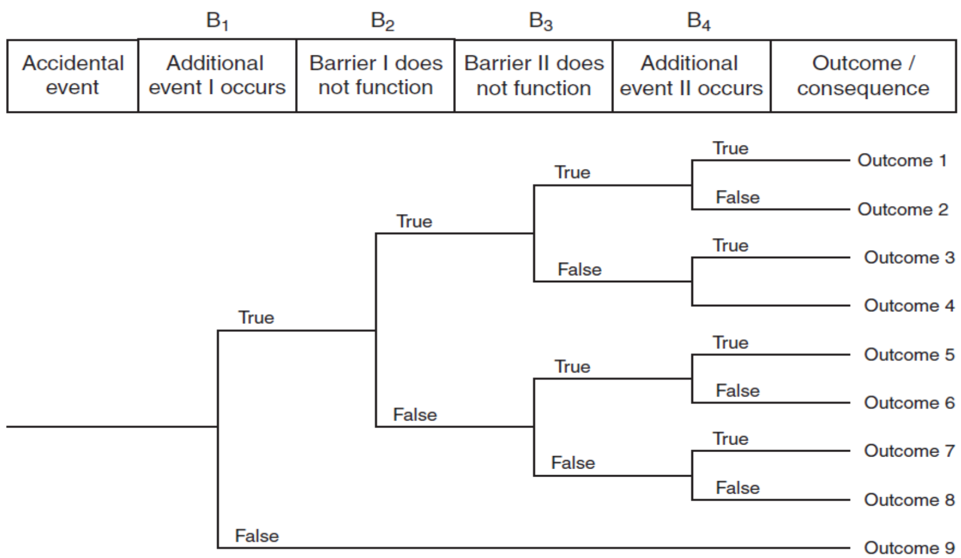

Figure 8: Event tree analysis (Adapted from Rausand, 2004).

2.7.5. Failure Modes Effects And Criticality Analysis (FMECA)

The FMECA is composed of two separate analysis, the Failure Mode and Effects Analysis (FMEA) and the Criticality Analysis (CA). The FMEA analysi different failure modes and their effects on the system while the CA classifies or prioritizes their level of importance based on failure rate and severity of the effect of failure (Department of the Army, 2006).

2.7.5.1. FMECA benefits

FMECA is a method used as a failure assessment technique to determine the reliability of equipment and system. This method, used since the 1960s in aeronautics, has since been extended to many areas of industry. The FMECA enables the systematic study of the causes and effects of failures that affect the components of a system. According to Department of the Army, 2006 The FMECA will :

(i) highlight single point failures requiring corrective action;

(ii) aid in developing test methods and trouble shooting techniques;

(iii) provide a foundation for qualitative reliability, maintainability, safety and logistics analyses;

(iv) provide estimates of system critical failure rates; and

(v) provide a quantitative ranking of system and/or subsystem failure modes relative to mission importance;and

(vi) identify parts & systems most likely to fail. The Criticality Analysis (CA) provides relative measures of significance of the effects of a failure mode,as well as the significance of an entire piece of equipment or system, on safe, successful operation and mission requirements.

In essence, FMECA it is a tool that ranks the significance of each potential failure for each component in the system's design based on a failure rate and a severity ranking (Department of the Army, 2006). A typical FMECA flow is shown in Figure 9.

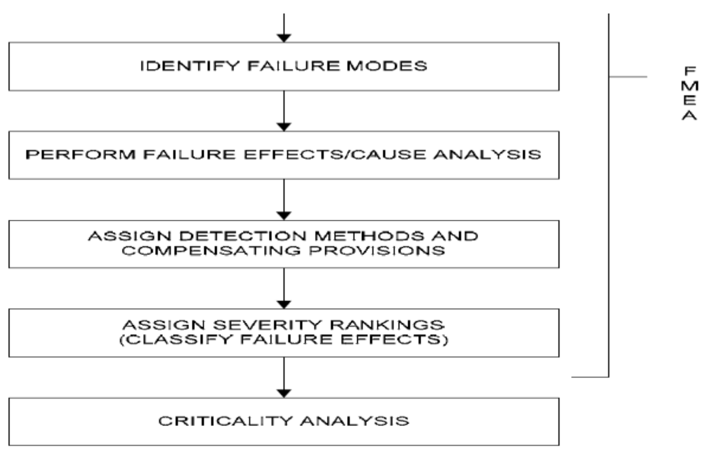

Figure 9: Typical FMECA flow (adapted from Department of the Army, 2006).

2.7.6. Reliability

Reliability is the capability of a product (or a system or a service) to perform its expected duty under the specified conditions of use over an intended period of time (Misra, 2008).

2.7.6.1. Reliability history

In science history, when it came to studying uncertainty and its consequences, the word that came up was "reliability". This developed with high-tech systems (weapons, nuclear power plants, aerospace, etc.) and was an end. Today, "reliability" has become a key quality parameter and as a decision aid in the study of most"consumer"components, products and processes. In addition, this concept of reliability has had to adapt, and it has been associated with other concepts such as availability, maintainability, security and others.

The combination of Reliability, Availability, Maintainability and Safety methods and tools has formed since the1980s a scientific corpus called Operational Safety (FMDS). Table 1 makes a compilation of the history around the reliability.

Table 1: Reliability history

Historical Year	Concepts	Description
1930	First concepts and theories	The increasing use of electricity and the need to make this source of energy more reliable have led to the discovery of the importance of redundancies from a reliability point of view.
1940	Lusser's and Murphy's Laws	During the war, the Germans built the first predictive reliability models for their missile project. This study showed the absurdity of the existing theory, and the mathematician Pier Uschka established the new so-called Lusser's law on the reliability of a series assembly.
1950	Safety in the nuclear industry and aeronautics, human reliability	The maintenance cost is then very much higher than that of the equipment as a result, a new concept was born, it is better to design reliable equipment rather than wait for failure. Thus, a series of tests took place before the industrialization of a component in order to determine certain parameters of operational safety. It was in this decade when the human error and on safety in the nuclear Industry and aeronautics appeared.
1960	Appearance of methods, tools and standards	This period corresponds to the beginning of detailed analysis of failures and their effects from the point of view of availability or safety with the development of the FMEA method (Analysis of Failure Modes and their Effects) by aeronautics
1970	Integration of the human factor and software reliability	Other axes developed in the 1970s such as human reliability and software reliability, In Japan, quality circles are multiplying and allow the identification, analysis and resolution of quality and Safety problems
1980	Maintainability and Availability Concepts	During this decade, new concepts were considered: maintainability and availability of equipment, Reliability, maintainability, availability, and security are the four components of dependability

2.7.6.2. Strategy in Reliability Engineering

According to Misra (2008), the prioritized objectives of reliability engineering are:

(i) To apply engineering knowledge to understand and anticipate the possible causes of product or system failures and to take adequate measures to prevent them from occurring;

(ii) To identify and check the failure mechanisms, which eventually lead to failures;

(iii) Explore the ways of reducing the likelihood or frequency of failures despite the efforts to prevent them; and

(iv) To apply methods for estimating the reliability of new designs, and for analyzing reliability data with a view to improve future designs.

Basically, reliability engineering is the first and foremost application of good engineering, in the widest sense, during design, development, manufacture and use (Misra, 2008).

CHAPTER 3 - 3. COMPANY OVERVIEW AND METHODS

3.1. Company Overview

Mozal is aluminium smelter Pechiney technology project, in the concept it was estimated the project funding to be US$ 1182 million (Mozal History, 1999). Mozal is an aluminum smelting company that has been operating in Mozambique since 2000. Like any other aluminium production industry, the process of obtaining aluminium at Mozal occurs by reducing calcined alumina in electrolytic vats at high temperatures, in a process commonly known as Hall-Heroult. Meanwhile, operations in the company's reduction section have suffered constant interruptions due to constant breakdowns in the main process equipment, a situation that somehow compromises the normal course of production activities. Mozal smelter project was sustainable to be initiated in Mozambique due to the following factors:

(1) **Well on Road to Political Recovery**-Mozambique was independent country after the war of 16 years this was sustainable for Mozal project;

(2) **Abundance of Manpower**-Mozal needed a lot of manpower to run the project and Mozambique has abundance in terms of manpower due to lack of industries and availability of people. Mozal direct employees is around 1089 (Mozal presentation, 2003);

(3) **Mozambique to Become less Dependent on Foreign Aid** – Mozal helped Mozambique to be less dependent by increasing gross domestic product. In 2002 real Gross domestic product growth 8% (Mozal 2.1%), net positive impact on balance of payments around $100m at steady state Mozambique export earnings US $220m to US $1bn (Mozal presentation, 2003);

(4) **Competitive Priced Power-** Mozal consumes 900mW Four times Mozambique's total Consumption by that period of conception, which matched with the availability from Cahora Bassa (Mozal presentation, 2003);

(5) **Maputo Closest Port to SA-** Matola Aluminium Terminal opened in March 2000 with capacity of 1 200 000 tons of raw materials and 506 000 tons of export (Mozal presentation, 2003).

3.1.1 Main departments

3.1.1.1. Operations Departments

Carbon, Reduction, Cast house, Treatment & Logistics, Maintenance, Engineering.

3.1.1.2. Service Departments

Human Resources, Finance, HSE, Corporate Affairs, Supply.

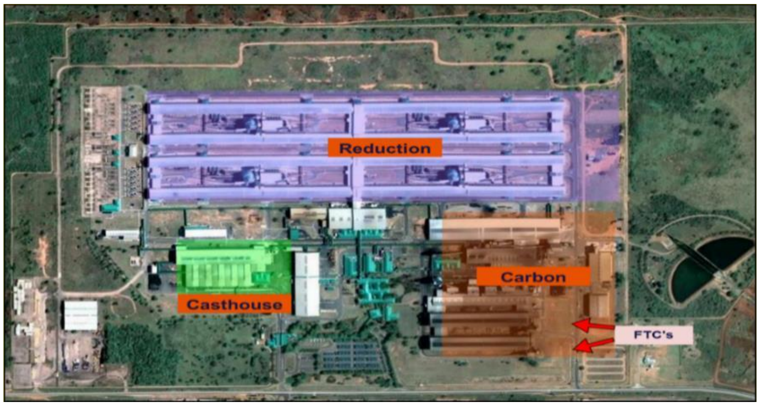

Figure10: Mozal Reduction Department overview (adapted from Mozal General Safety Induction Manual, 2019).

3.1.2. The reduction department – brief introduction and equipment used

The Reduction area is the main production plant at Mozal, it contains the 576 electrolytic cells (or pots) where the liquid aluminium is produced. The process used is the Hall-Heroult process. The process uses approximately 360KA of direct current, carbon anodes and graphite cathodes to reduce Alumina to Aluminium Approximately 2700-2800kg of liquid aluminium is produced per pot per day or 560-570000T year (Reduction area specific induction manual, 2016).

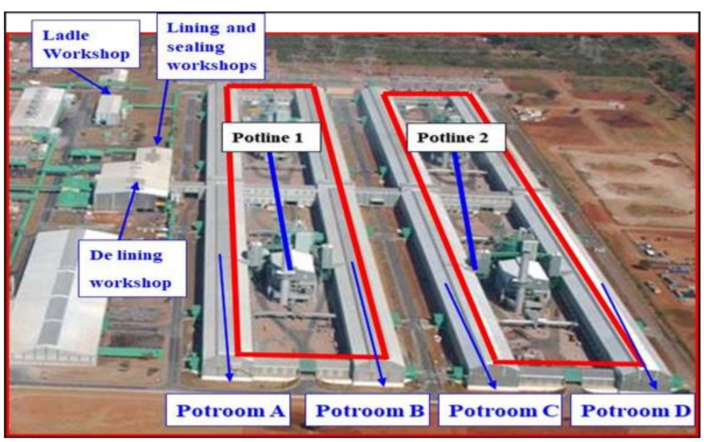

Figure11: Reduction department (adapted from Mozal General Safety Induction Manual, 2019)

PTA Pot tedding assembly (PTA) is the main equipment used in reduction department in aluminium production. PTAs are machines currently used in the aluminium industry for lifting and transporting load from one location to another in pot required activities, following three independent or combined movements, namely longitudinal, transversal and vertical, in certain applications, other movements may be included, the load swing and the operator's cabin. They are basically composed of girders (Bi girder), a cart, a hoist and winches and a range of tools. They are mounted on the factory walls or on columns along the sides of the pavilions, and for the purpose of manipulating classically large and heavy and cannot be moved easily.

Figure12: Pot tending assembly (adapted from Mozal General Safety Induction Manual, 2019)

3.2. Methods

Practical methods to estimate resilience are still scarce. In the present study was used one of the resilience calculation methods proposed by Caputo et al. (2019) applied in oil and gas industry. In order to enhance resilience in reduction department qualitative and quantitative analysis were proposed and these included fault tree analysis, event tree analysis, failure modes and criticality analysis and reliability. The main steps followed, and a detailed description of the methods is as follows.

3.2.1. Data collection

Relevant data to the research was collected in the operations section of the Mozal reduction department. Historical data on the number of breakdowns, the frequency with which these breakdowns occur, the impact caused by pot tending assembly in production, data on the current level of resilience, maintenance activities and their frequency, the downtime of the production process were collected. The process was carried out based on the reduction production and maintenance reports and this included: (a) PTA Monthly breakdown; (b) PTA Yearly breakdowns; (c) PTA Monthly downtime and (d) PTA availability.

3.2.2. Data processing and analysis

The analysis of collected data was carried out through risk management methods carefully selected according to the purpose of the study. Statistical tools were also used to complement the analysis, and, in the specific case, the MATLAB software was used. Some the methods indicated herein are described below:

3.2.2.1. Calculation of resilience

From the information gathered on production after two following shifts of breakdown the Caputo et al. 2019) formula (equation 3) was used to calculate the resilience of operations in Reduction Department.

$$Resilience = \frac{1}{t_r - t_0}\int_{t_0}^{t_r} C(t)dt \qquad (3)$$

where:

t_r is recovery time

t_0 is breakdown initial time

3.2.2.2. PTA Functional analysis

Functional analysis method is used to understand the functions and important components of the studied equipment, including its external environment. In this study the targeted equipment is the pot tedding assembly (PTA) system, which is the main system used in reduction department in aluminium production.

3.2.2.2.1. Elementary system

Bath ladle lifting beam (BLLB), Metal ladle lifting beam (MLLB) and Beam raising frame are the main elementary systems allocated to reduction department. BLLB is connected to the main PTA system to tap electrolytic bath. MLLB is also connected to the main system to tap aluminium. Beam raising frame is connected to the main system to raise the beam of the electrolytic cells (Pot).

3.2.2.2.2. Interface

In interface between system and elementary system connections by electrical plug and air plug is used.

3.2.2.2.3. Environment

The environment temperature has an impact to the system to consider.

3.2.2.2.4. PTA Components

The PTA system is basically composed of an air compressor, hydraulic system and electrical components as shown in Figure 13.

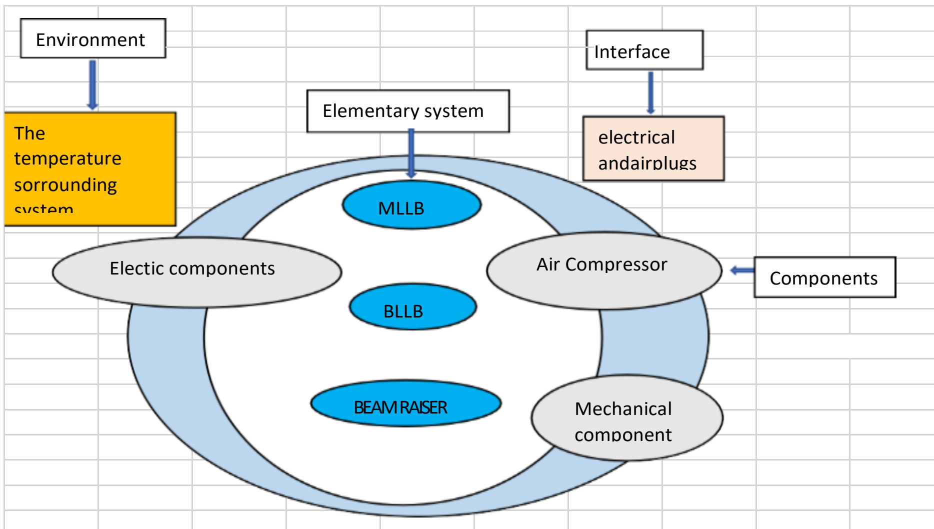

Figure 13: PTA main components

3.2.2.2.5. External components that are in interaction with the product

The external components of PTA are:

Weather, Storm/heath quake, Electricity, Air, Load, Pot, Aluminium, Tools, Components, Operator.

Figure 14 summarizes the relation between external components with the product (PTA). From here it is possible to identify the different functions necessary to the desired objective of producing aluminium.

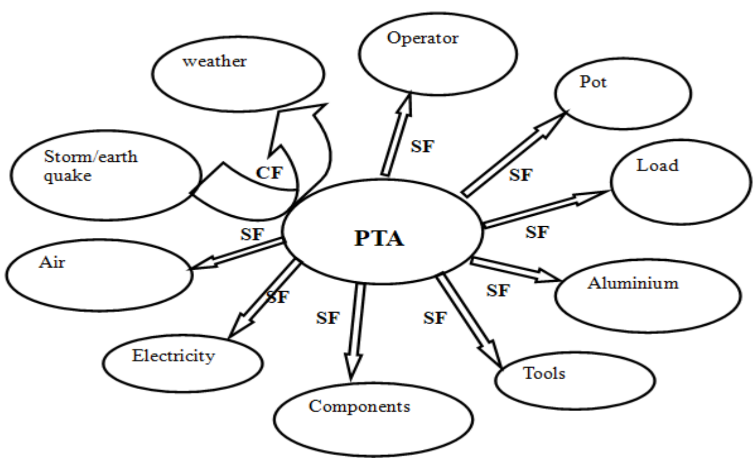

Figure 14: Relation between external components

3.2.2.2.6. List of necessary functions

F1 - To produce aluminium

F2 – To attend the pot

F3 - Lifting load

F4 - By operator

F5 – Using tools

F6 - By pneumatic and hydraulic system

F7 - By using compressed air and hydraulic oil

F8 - Produced in air compressor and power from hydraulic unit Connected to electricity

3.2.2.2.7. Specification of the functions

For functions classification by degree of importance was used Mudge Matrix as shown in Table 2. As recommended by the method a scale of weight from 1 to 3 to make comparisons between them was determined, where:

1 - Function slightly more important than other (in comparison with)

2 - Function for sure more important than other (in comparison)

3 - Function much more important than other (in comparison)

Table 2: Comparison of the functions in pairs.

	F2	F3	F4	F5	F6	F7	F8	Weight	%
F1	F1 1	F1 1	F1 1	F1 1	F1 1	F1 1	F1 1	7	15.5
F2		F2 1	F4 1	F2 2	F2 2	F2 2	F2 1	8	17.7
F3			F4 3	F5 3	F6 3	F7 3	F8 3	0	0.0
F4				F4 3	F4 2	F4 1	F4 1	8	17.7
F5					F6 3	F7 2	F8 2	3	6.6
F6						F7 1	F8 1	6	13.3
F7							F8 2	5	11.1
							F8	8	17.7
							Total	45	100

3.2.2.2.8. Importance of functional analysis

The functional analysis of a product or system is important to:

- Develop a shared understanding of the project.
- Identify missing functions.
- Define, simplify and clarify the problem.

- Organize and understand the relationships between functions.
- Identify the basic function of the project, process or product. Improve communication and consensus.
- Stimulate creativity.

3.2.2.3. Failure Modes, Effects and Criticality Analysis (FMECA) of PTA

After the main system was studied, the failure mode of the system was also analyzed in order to calculate the level of criticality of each failure mode.

3.2.2.3.1. Criteria and associated values

The study of the effect of each failure on the system was conducted and assigned to each listed fault based on severity, frequency and control as shown in Tables 3, 4 and 5.

Table 3: Severity of the failure mode.

Criteria	Associated value
Fatality/considerable material damage	10
Serious injury/ very significant material damage	8
Slightly injured/significant material damage	6
Significant material damage	4
Minor material damage	2

Table 4: Frequency score of failure mode.

Criteria	Associated value
Less than a week	10
Less than one month	8
Less than one year	6
Less than ten years	4
More than ten years	2

Table 5: Control score for failure modes.

Criteria	Associated value
No action possible	10
No known control	8
Check not guaranteed	6
Average control	4
Good control	2

3.2.2.3.2. Criticality calculation

Criticality Analysis is a method which is used to understand and know the criticality of failure modes and the effects derived from the maintenance process of the system under study. The criticality is calculated based on severity, frequency and control of the failure mode, where:

$$Criticality = severity \times frequency \times control$$

3.2.2.4. Fault tree and event tree

Fault and event tree analysis was used to develop scenarios that can lead to unexpected events and will allow analyzing their effects and their mitigation. The fault tree is used to analyze what can lead to the occurrence of an unexpected event and, in turn, the analysis of event trees makes the analysis of the consequences of an event that occurs if certain measures or conditions are not observed or fulfilled. For the PTA breakdown, the fault tree and event tree analysis can be made via probabilities calculated using Boolean algebra equation as shown below:

$$Mechanical\ problems \cup Electrical\ problems = PTA\ Breakdown$$

3.2.2.5. PTA Reliability

Through the data collected from the maintenance process of the system under study, a calculation model was used to understand how reliable the PTAs are. The method was used to assess equipment reliability through calculations of component failure rate, mean time to failure, and component and system reliability.

Reduction department is composed by 20 pot tending assemblies (PTAs) in which at least 16 must be operational but most of time even 16 do not work, they are in breakdown. It is well known that low reliability has negative consequences like increased costs derived from replacing or repairing components with failures. But low reliability can also lead to a decrease in safety (Joao de Oliveira 2015). At Mozal reduction department safety issues caused by low reliability are fatigue of operators and maintainers due to the high workload of worker when excessive breakdowns occur. So, by analyzing the PTA reliability it will be possible to recommend to the maintenance team at which stage preventive maintenance can be performed on the equipment to avoid failures. So, the intervals that the PTA preventive maintenance is of 1500 hour; 3000 hours; 4000 hours and 6000 hours. Based on this maintenance schedule the reliability of the PTA system was calculated.

3.2.2.5.1. Representation of reliability diagram of the system

Based on the components seen in functional analysis of PTA, the system components are in series, the failure of one of the blocks causes the failure of the system. The reliability of the system is lower than the reliability of the least weak block.

PTAs1-Electric components

PTAs2-Pneumatic and Hydraulic components

PTAs3-Mechanic components

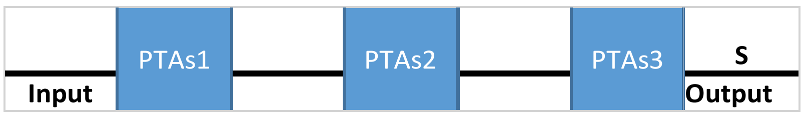

Figure 15: PTA System block diagram.

3.2.2.5.2. Reliability of three components in series with different reliability

The PTA as seen in the functional analysis has mechanical, pneumatic, electrical and hydraulic system, so the reliability was analyzed based in these components. The PTA system components are connected in series because when one of the components does not work the whole system will not operate, based on that the formulas applied to calculate reliability of components and that of the system were developed.

3.2.2.5.3. Formulas to calculate relibility

Reliability is generally measured by the probability that an entity E performs a required function, under the given conditions, during the time interval [0, t]: R (t) = P [E not failing on [0, t]], and failure rate probability that the entity fails between during interval of time. The formulas below refer to calculate the reliability of PTA components, reliability system, instantaneous failure rate and Mean time to failure.

Equation 4:Reliability of component

$$\boldsymbol{reliability\ of\ component} = R_i(t) = \exp(-\lambda_i t) \tag{4}$$

Where:

$R_i(t)$ is the reliability of a component

λ_i is instantaneous failure rate of component *i*.

Equation 5: System reliability

$$\boldsymbol{System\ reliability}\ is\ R(t) = \Pi_i^n = 1R_i(t) = \exp\left(\left(-\sum_{i=1}^{n}\lambda_i\right)t\right) \quad (5)$$

Where:
$R(t)$ is the Reliability of the system

Equation 6: Failure rate calculation

$$\lambda = \sum_{i=1}^{n}\lambda_i \quad (6)$$

λ is instantaneous failure rate of the system

Equation 7: Mean time to failure

$$MTTF = 1/\sum_{i=1}^{n}\lambda_i \quad (7)$$

Where:
MTTF is the mean time to failure

The failure rate was calculated based on MTTF obtained for each component in the PTA maintenance which are 1500hours, 4000hours and 6000hours for PTAs1, PTAs2, PTAS3 respectively. Where PTAs1;2;3 is PTA component.

PTAs 1 failure rate = 1.6E-04,PTAs 2 failure rate = 2.5E-04,PTAs 3 failure rate = 6.6E-04

CHAPTER 4 - RESULTS AND DISCUSSIONS

4.1. PTA Maintenance results

4.1.1. PTA yearly breakdowns

Figure 16 shows the number of breakdowns from 2015 to 2021. As can be seen, from 2015 to 2017 the number of breakdowns dropped significantly, having reached almost 34% reduction in 2017. In the following two years, that is, from 2017 to 2019, the situation remained practically unchanged. One year later, the reduction almost reached 40% compared to the reference year, 2015. The analysis made here did not consider the year 2021 because the data collected refer to 3 months only. The reduction shown in the figure is due to the intense maintenance work, however the results indicate that there is still a lot of work to be done, as the number of breakdowns remains significant. The maintenance schedule, including its quality, the poor quality of spares, poor operating procedure or useful life of equipment, PTA operation by production side could be behind this situation,

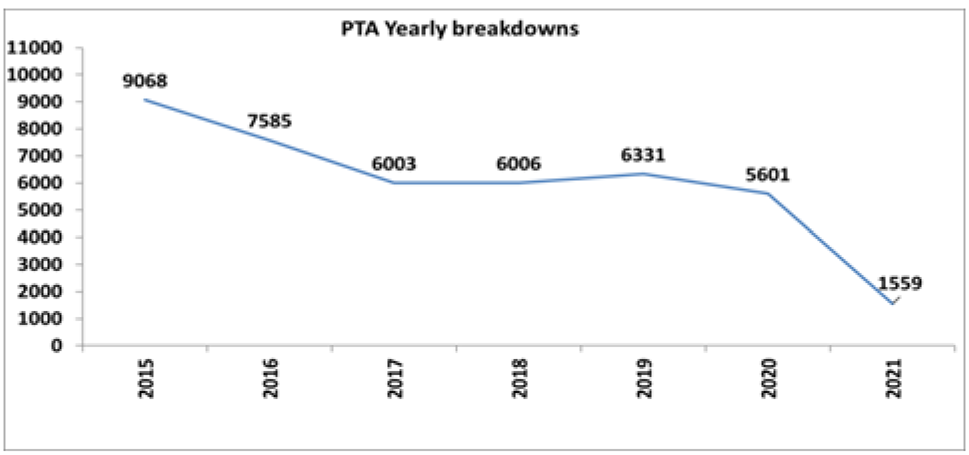

Figure 16: PTA Yearly breakdowns (Source: Mozal maintenance report, 2021).

4.1.2. Monthly breakdowns

Figure 17 shows number of monthly breakdowns of the PTAs, considering a period of time of 6 months (from October 2020 to March 2021). The figure leaves a clear indication that the monthly breakdowns of the PTAs are significant. With the exception of PTAs 06 and 09, all the others have more than 100 monthly breakdowns. The problems behind this situation are the same as those listed in the previous section.

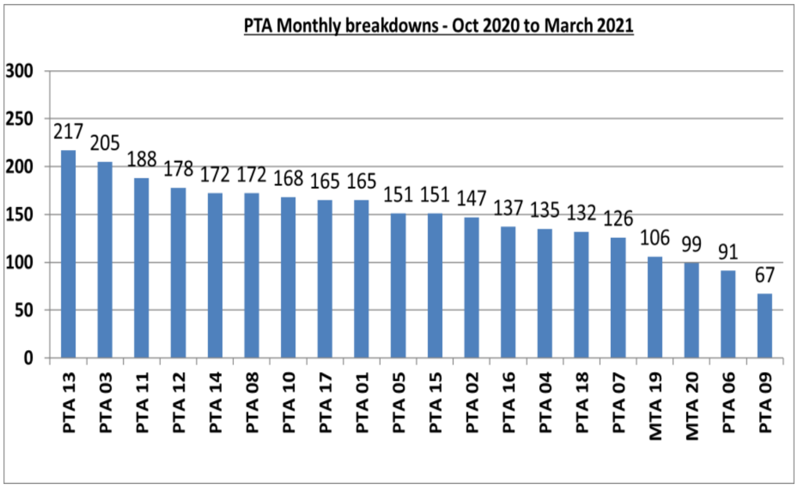

Figure 17:PTA monthly breakdown (Source: Mozal maintenance report, 2021).

4.1.3. PTA Monthly downtime

As expected, the number monthly downtime of the PTAs follows the same trend when compared to the number of breakdown. Similar to the number of breakdowns, the number of downtime in 2020 has dropped considerably by almost 21% when compared to when the stops peaked in 2017.

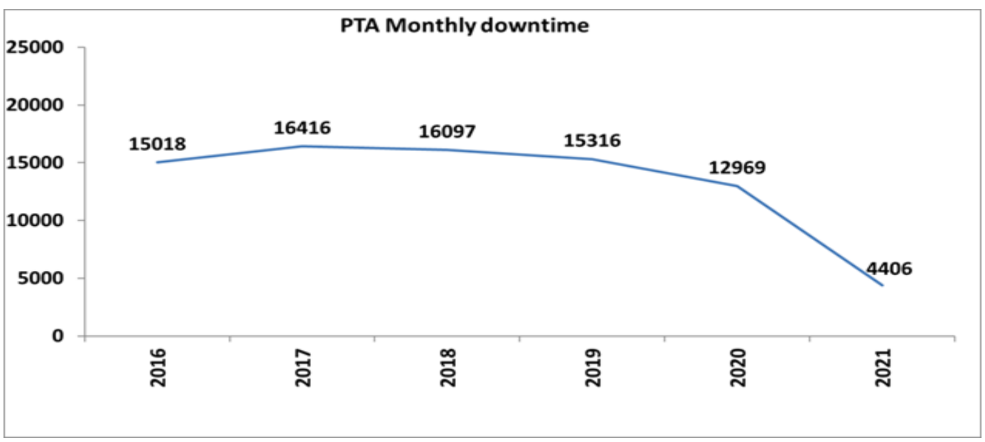

Figure 18:PTA monthly downtime (Source: Mozal maintenance report, 2021).

4.1.4. PTA Monthly downtime versus targeted number

Given the characteristics of the aluminum ingot production process, breakdowns and stoppages are always expected. Figure 19 shows the PTAs downtime of six months (November 2020 to 2021) versus targeted number of monthly downtime, in hours. As can be seen from the figure, despite the effort made in preventive maintenance, the number of monthly downtime in December 2020 and January, February and March 2021 was massive and above the targeted number, which is 1140, meaning that there were more breakdowns than expected.

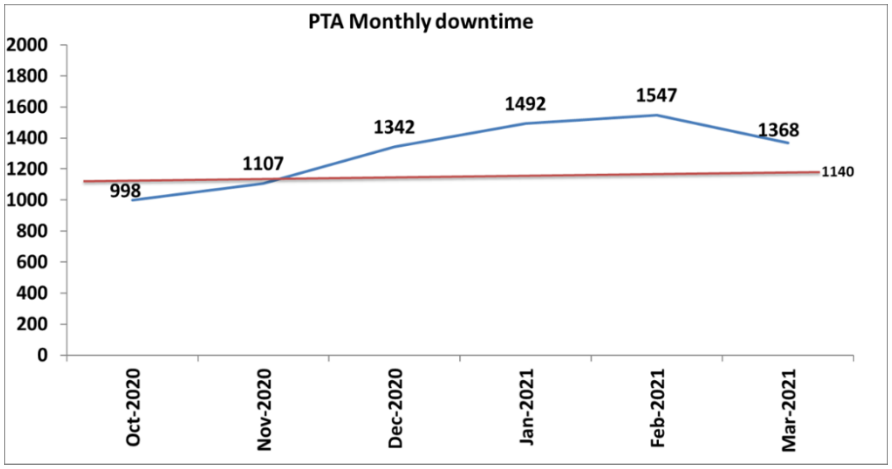

Figure 19:PTA Monthly downtime versus the targeted number (Source: Mozal maintenance report, 2021).

4.1.5. PTA Monthly availability

Availability is the ability of an entity to be able to perform a required function under given conditions, at a given moment or during a given time interval, assuming that the supply of the necessary external means is assured. Figure 20 shows the degree of availability of the process versus the targeted monthly availability (90%) for an evaluation made for a period of 18 months. As can be seen, despite the massive breakdowns and downtime recorded, of the 18 months evaluated, in just 3 months (December 2019 and January and February 2021) the process was below target parameter.

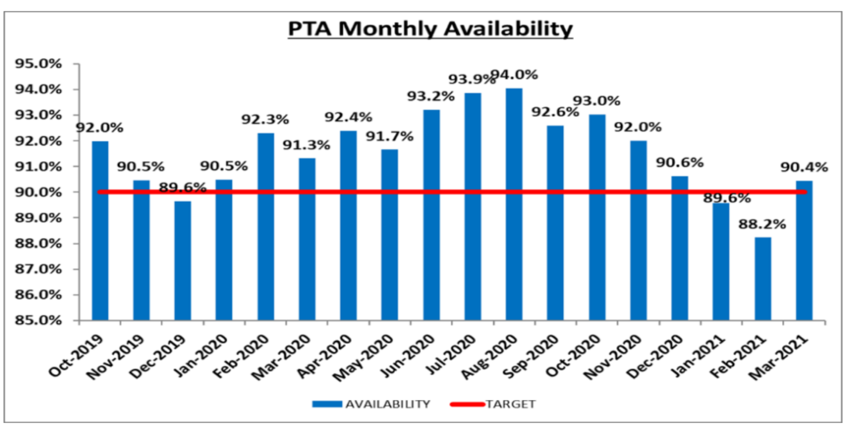

Figure 20:PTA Monthly availability (Source: Mozal maintenance report, 2021).

4.2. Reduction production results

Reduction production report helps to understand how long the breakdowns take to be fixed and the impact of them to production in terms of late operation. Table 6 shows the duration of breakdowns for a total of 9 PTAs analyzed for a 12-hour shift (from 7AM to 7PM). It can be seen from the table that 4 of 9 PTAs fail during 12-hour shift. The cumulative breakdowns duration were 23 hours, with an average of almost 6 hours per shift and per PTA, with a very negative impact on the production process for the company, resulting in late operations as shown in Table 7.

Table 6: PTA Breakdown for 12-hours shift

EQUIPMENT(PTA)	OPERATION DURATION (HOURS)	DURATION OF BREAKDOWN (HOURS)
MTA19	12	0
PTA04	12	0
PTA05	12	0
PTA16	12	0
PTA02	12	0
PTA14	12	4
PTA01	12	6
PTA11	12	6
PTA09	12	7
TOTAL BREAKDOWN DURATION (HOURS)		23

Table 7: Late operation caused by breakdowns

PTA TASK	SECTION		GRAND TOTAL
	POTROOM C	POTROOM D	
Anode change	0	9	9
Metal tapping	0	0	0
24 hours covering	0	6	6
4 hours covering	0	0	0
Beam raising	0	0	0
Bath to tap	0	0	0

4.3. Resilience assessment

Using equation 3, as indicated below, the process resilience can be calculated.

$$Resilience = \frac{1}{24-7}\int_{7}^{24} C(t)dt = 15.5\text{hours}$$

As can be seen, the Reduction operations are resilient, in 15.5 hours. This level of resilience is reached thanks to the enormous effort and commitment of the work teams that seek at all costs to keep the process operational through maintenance activities. This level of resilience however, can be improved and this can be done using qualitative or quantitative methods, thus saving workers stress.

4.4. PTA Function percentage vs its relevance

According to functions analysis of PTA, all the functions are relevant. As result of comparison it was obtained the relative percentage of each function as shown in Figure 21, which is important step for the specification of the degree of importance of each function in the product. Based on the weight percentage of the function, the histogram was prepared (Figure 21). This was then subdivided on a scale (k) from 1 to 5 to specify the relevance of each function in the system, classified as follow : 1 - Useful; 2 – necessary; 3 – Important; 4 - Very important; 5 – Vital. From the histogram, is possible to observe that the F1, F2, F4 and F8 present a high percentage of weigh, so there are classified by vital and very important functions for the process.

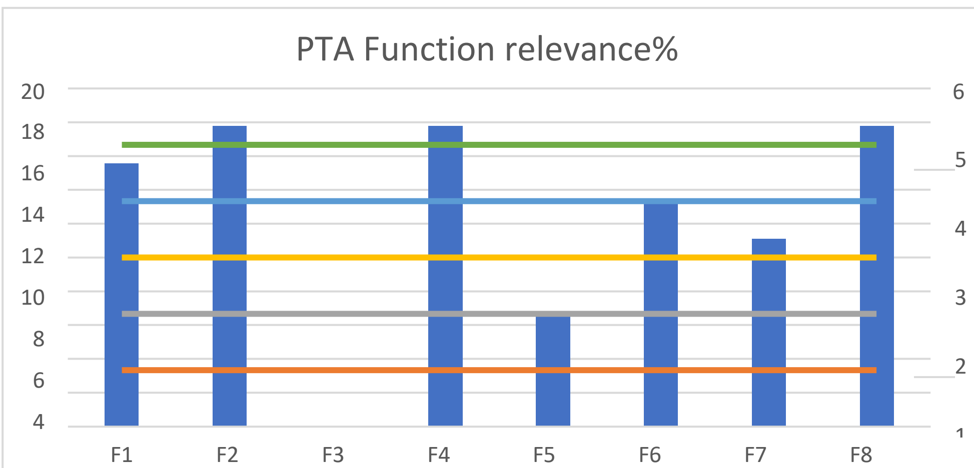

Figure 21: Function percentage vs its relevance

4.5. Fault tree and event tree

The event tree and fault tree scenarios were developed to analyze what are the consequences that can be caused by breakdowns and what are that probable causes of the failure of PTA that when preventive maintenance is performed can be possible to prevent them.

4.5.1. Fault tree analysis results

In fault tree the probability of mechanical fault and electrical fault to occur is of 0.095 as show in Figure 22, which in terms of fault tree analysis is very high.

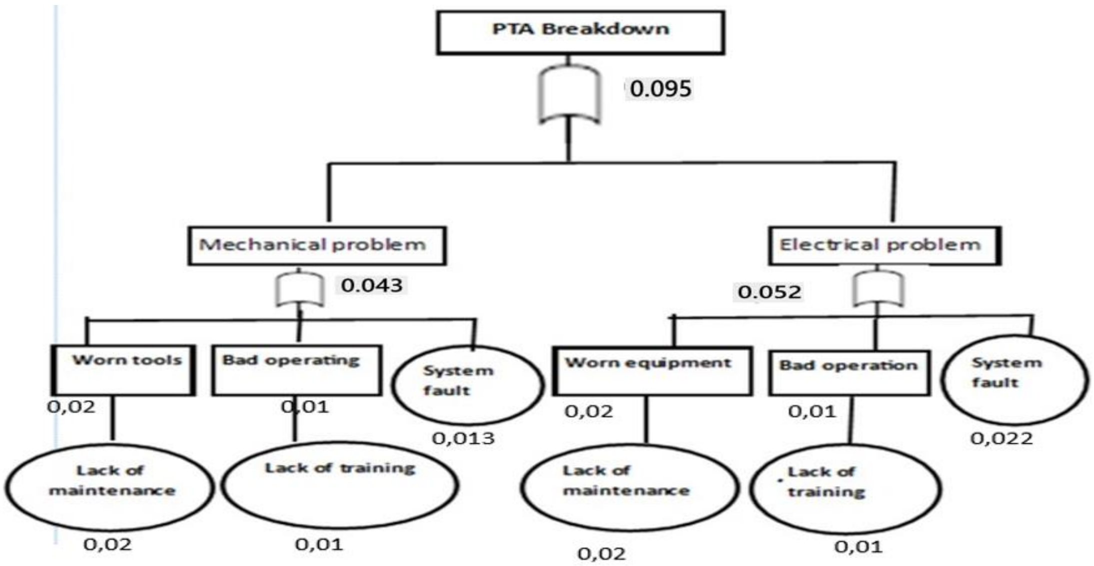

Figure 22: PTA Breakdown fault tree analysis.

From the figure it can be seen that the PTA breakdowns can be caused by mechanical and electrical problems and the probability of these faults is 0.095, which is high due to combination of the functions of PTA system that if one system fails then the PTA doesn't work. But, by doing preventive maintenance such as replacing worn components, providing training to operators, adoption of other types of maintenance methods, the breakdowns may be prevented.

4.5.2. Event tree analysis results

The event tree was used to analyze the consequences of PTA breakdowns and occurrence probability of successive events when breakdown occur. From Figure 23 it is clear that when the successive events are not effective like early warning of breakdown, maintenance intervention, plan to mitigate and emergency plan then the consequence of breakdowns is late operations and fatigue of personnel working hard in order to fix the breakdown. The occurrence probabilities were (Figure 23) 0.778, 0.067, 0.044, 0.009 and 0.1, respectively for no late operations (first way), no late operations (second way), moderate late operation (third way), late operations (fourth way), and late operation and fatigue (fifth way).

From event tree creativity can be developed to introduce breakdown early warning in order to anticipate the failure in PTAs. However, Pasman and co-workers (2020) propose error tolerant design to increase resilience and one of the errors tolerant is early warning. Early warning is for impending threat and risk is of great significance. Using different tools to measure normal equipment operationality can trigger an alarm to show the abnormality in equipment, based on vibration, energy consumption, corrosion, maintenance service, etc. By having a system like centralized maintenance management system (CMMS) and laboratory information management system (LIMS) updates that are of significance can be provided. By having also enterprise resource planning (ERP) information, such as system analysis and program development (SAP) data on the company business processes (accountancy, client orders, suppliers, maintenance schedules, and logistics) will help significantly. Finally, and not the least, the lagging and leading process safety performance indicators (CCPS) data can be gauged, which can provide useful information on trends in the quality of the safety management system, safety culture, and resulting safety climate (Pasman et al, 2020).

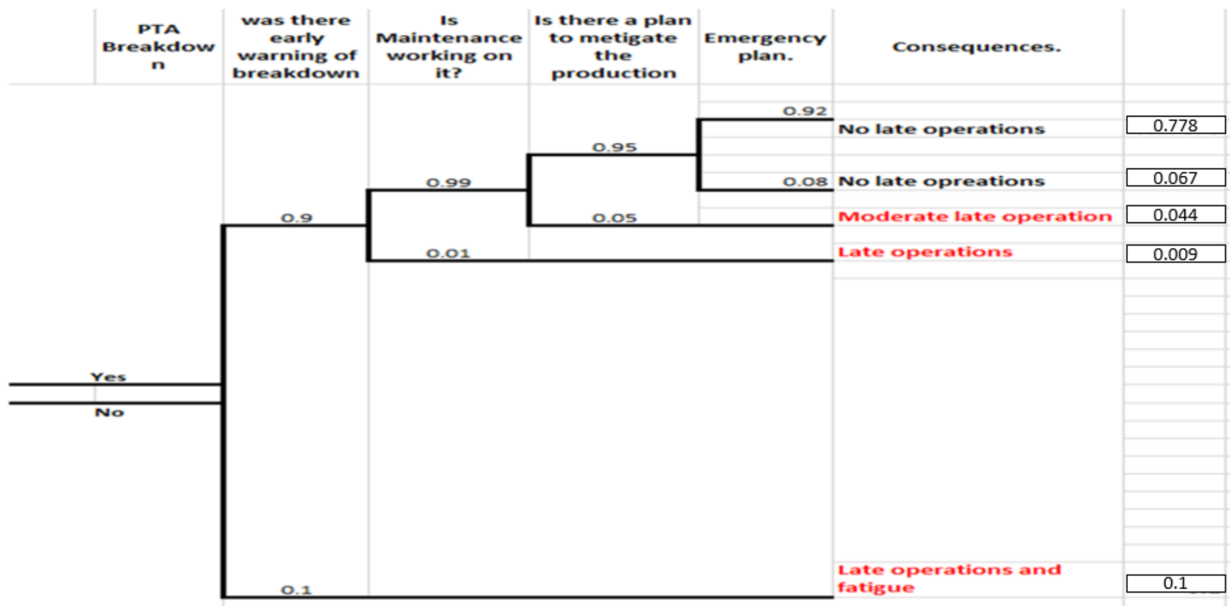

Figure 23: Event tree analysis.

Mozal company uses a SAP system. However, the scheme showed in Figure 24 could be recommended to be used at Mozal linked to SAP in order to alert from repetitive breakdowns or tendence that PTA have to go under breakdown. The overall analysis of survivability for the company with the objective to prevent escalation of breakdowns, given maintenance options and final optimization, have to follow the scheme shown in Figure 24.

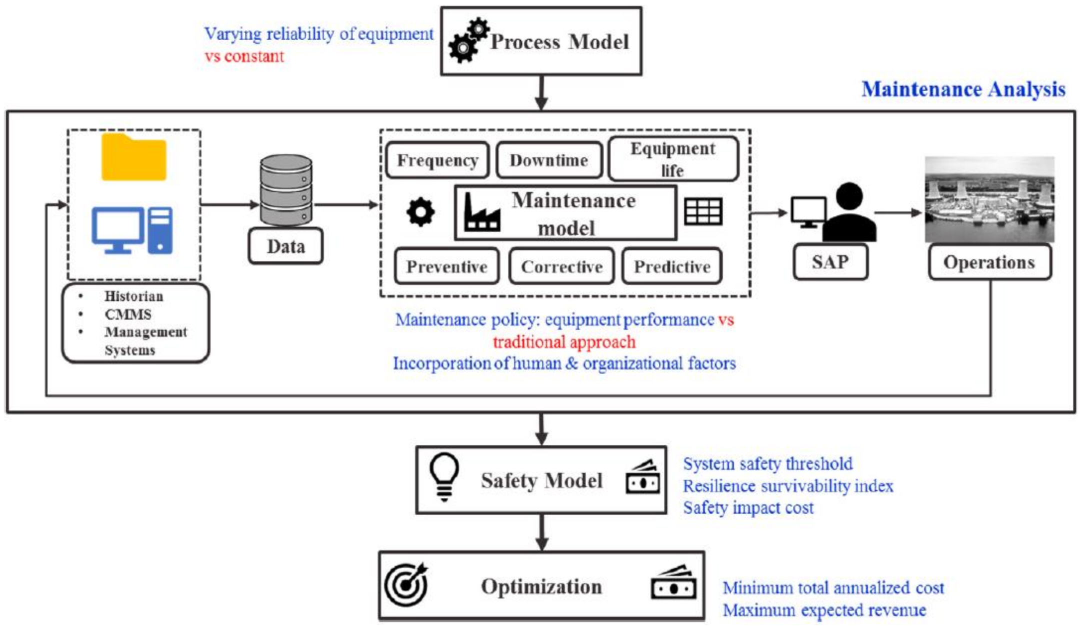

Figure 24: Maintenance optimization scheme (Source: Pasman et al., 2020).

4.6. Failure modes effects and criticality (FMECA)

Figure 25 shows the Top 10 failure modes for a period of time of 6 months (from October 2020 to March 2021) for PTA 3, 8, 9, 11 and 13, being the insulation or voltage fault the failure mode that leads the list. Table 8 presents the criticality results showing possible causes, the degree of criticality and describing in what ways the PTA fail to fulfil its functions.

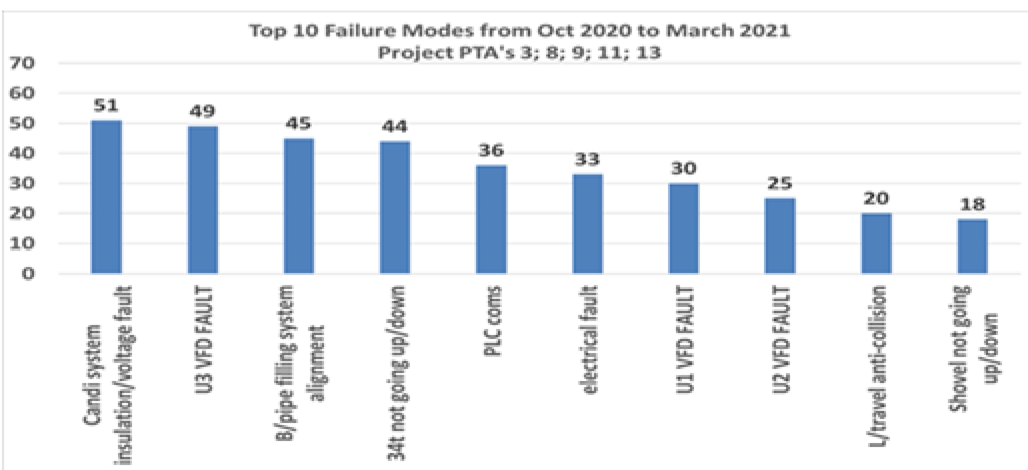

Figure 25: PTA Failure modes (Source: Mozal maintenance report, 2021)

From Table 8 it can be seen that the insulation or voltage fault and B.pipe or filling station alignment are the most critical failure modes, both with 120, with electrical failures being the main causes. However, despite the high degree of criticality for these two types of failure modes, the severity is set at 2, indicating minor material damage and the frequency score set at 6 (less than one year).

Table 8:PTA criticality analysis elaborated based on maintenance information

Component	Functions	Failure modes	Possible causes (internal and External	System effects	Severity	Freq	Control	Criticality
PTAs	To do pot operations	Insulation/voltage fault	Electric fault	PTA moving slow	2	10	6	120
		U3 VFD fault	Electric fault	PTA not moving	2	10	4	80
		B.pipe/filling station alignment	Electric fault	PTA not covering	2	10	6	120
		34T not going up/down	Mechanical fault	PTA not tapping	2	10	4	80
		PLC Comms	Electric fault	PTA not moving	2	10	4	80
		Electrical faults	Lack of maintenance	PTA not moving	2	10	4	80
		U1 VFD fault	Electric fault	PTA not moving	2	10	4	80
		U2 VFD fault	Electric fault	PTA not moving	2	10	4	80
		L/travel anticollision	Electric fault	PTA moving slow	2	8	2	32
		Shovel not going up/down	Mechanical fault	PTA not working	2	8	4	64

From the criticality analysis table and for better understanding and interpretation of the failure modes, a principal component analysis (PCA) can be done using MATLAB software. Figure 26, 27 and 28 show the failure modes PCA for 1st and 2nd, 1st and 3rd and 1st and 2nd and 3rd components. Figure 29 and 30 show the 2D and 3D analysis of failure modes associated values and criticality. As can be seen from Figure 26, 27, 28, 29 and 30, the criticality, frequency and severity (shown in the right side top corner of the figures) are very high, showing a clear indication that there is a need for maintenance intervention in order to lower the level of criticality of the components.

In figure 25 the failure modes represented in the left are the less critical followed by the failure modes in the right side bottom the most critical are at the right side bottom.

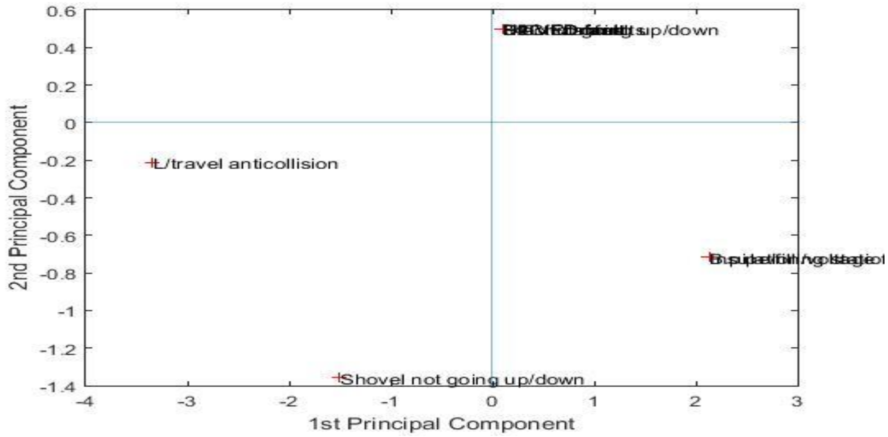

Figure 25: Failure modes PCA for 1st and 2nd components.

In the figure 26 the failure modes more to the left are the less critical and which are more to right quadrant are critical, the most critical are in the quadrant in the right side on top.

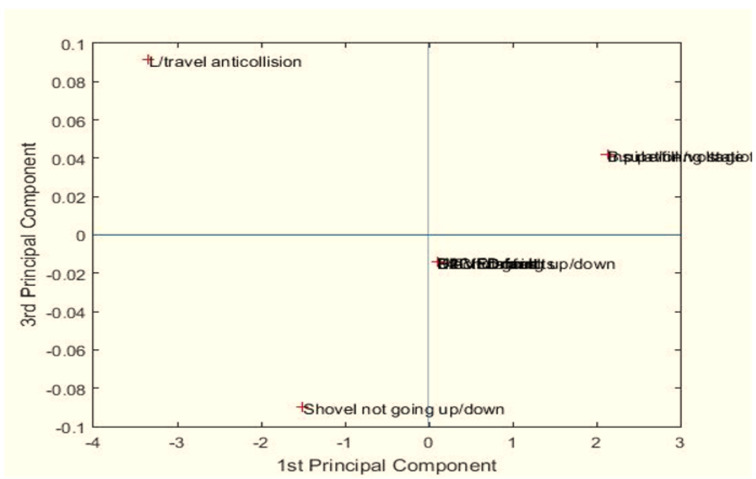

Figure 26: Failure modes PCA for 1st and 3rd components.

Figure 27 is the compilations of all the components first, second and third it shows in the same figure all principal components showed in figure 25 and 26 the analyze is based on the same principle more to the left less critical is the failure mode less critical it is.

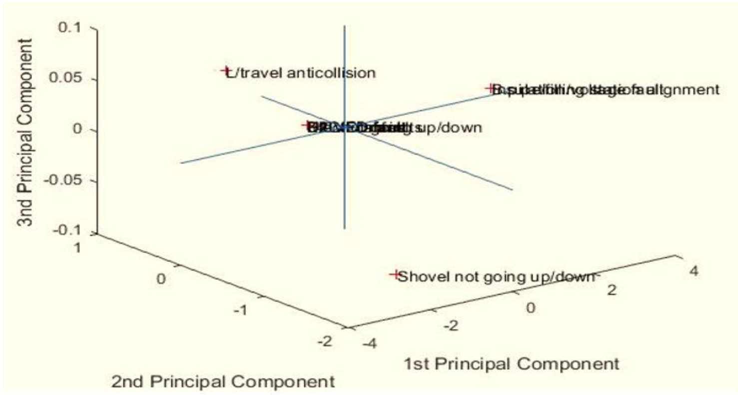

Figure 27: Failure modes PCA for 1st, 2nd and 3rd components.

Figure 28 shows the analysis of associated values in two dimensions, where the frequency of failure modes that are more to the right side on top have high frequency, at the right side bottom critical and control associated values are high, the severity is the same for all failure modes, reason why the severity is in the center of the figure.

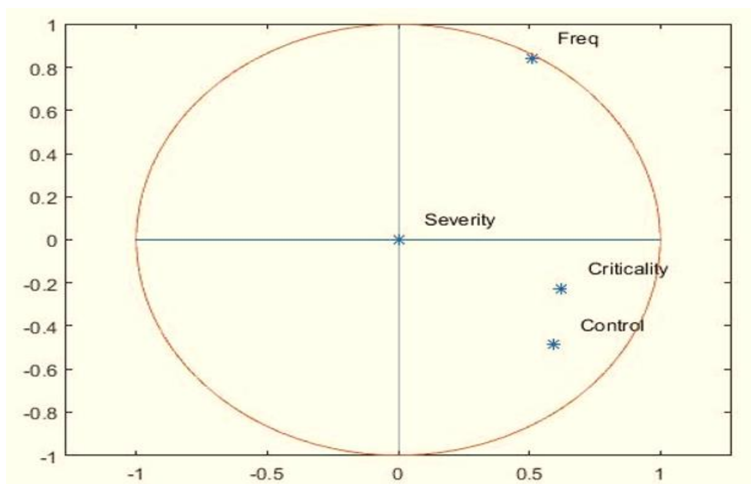

Figure 28: PCA 2D associated values and criticality analysis.

Figure 29 shows in three dimensions the associated values where the failure modes at the right top side are more critical the frequency is also high, severity is the same for all failure modes is in middle.

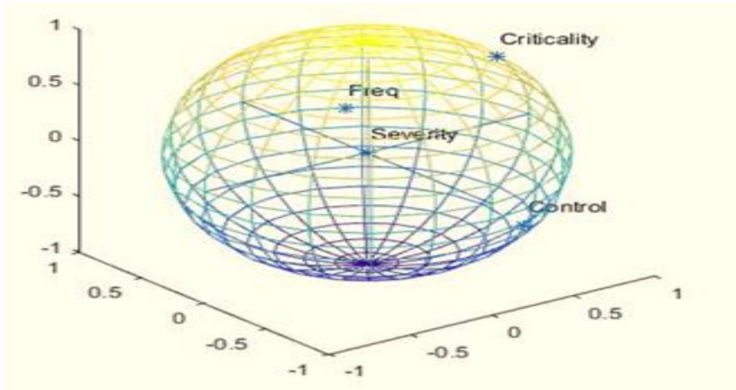

Figure 29: PCA 3D associated values and criticality analysis.

4.7. Reliability

4.7.1. Preventive maintenance in PTA according to reliability calculations results

Table 9 shows the results of the reliability calculations, showing the schedule, including days or date that the preventive maintenance in PTA needs to be done if the company does not want the reliability of the system to drop below 0.9. The table also shows what the reliability of the components will be at the certain day/date.

Table 9:PTA system and components reliability.

i	t (hours)	RPTA(t)	RPTAs1(t)	RPTAs2(t)	RPTAs3(t)
0	0	1	1	1	1
1	60	0.93	0.99	0.98	0.96
2	65	0.93	0.98	0.98	0.95
3	80	0.91	0.98	0.98	0.94
4	90	0.90	0.98	0.97	0.94
5	95	0.90	0.98	0.97	0.93
6	96	0.90	0.98	0.97	0.93
7	97	0.90	0.98	0.97	0.93
8	98	0.89	0.98	0.97	0.93
9	100	0.89	0.98	0.97	0.93

From the table 9 it can be seen that in order to avoided that the PTA system reliability (RPTA) do not drop below 0.9, then the preventive maintenance must be done at 97 hour after 4 days of operation and by that time the reliability of the components (RPTAs) will be: RPTAs1= 0,98, RPTAs2 = 0,97 and RPTAs3 = 0.93.

Figure 30 shows the reliability and mean time before failure (MTTF) of the system and components through failure rate of the components of the system calculated based on data collected from PTA maintenance. The maintenance report shows that despite the maintenance effort to reduce breakdowns, the number of PTA breakdowns, availability and downtime is still very high, and this may be due to the point in which maintenance act in terms of PTA reliability, based on the reliability calculated using maintenance schedule. The maintenance, therefore, may adopt the proposed reliability schedule so that the reliability may not drop up to lead a breakdown on the PTA.

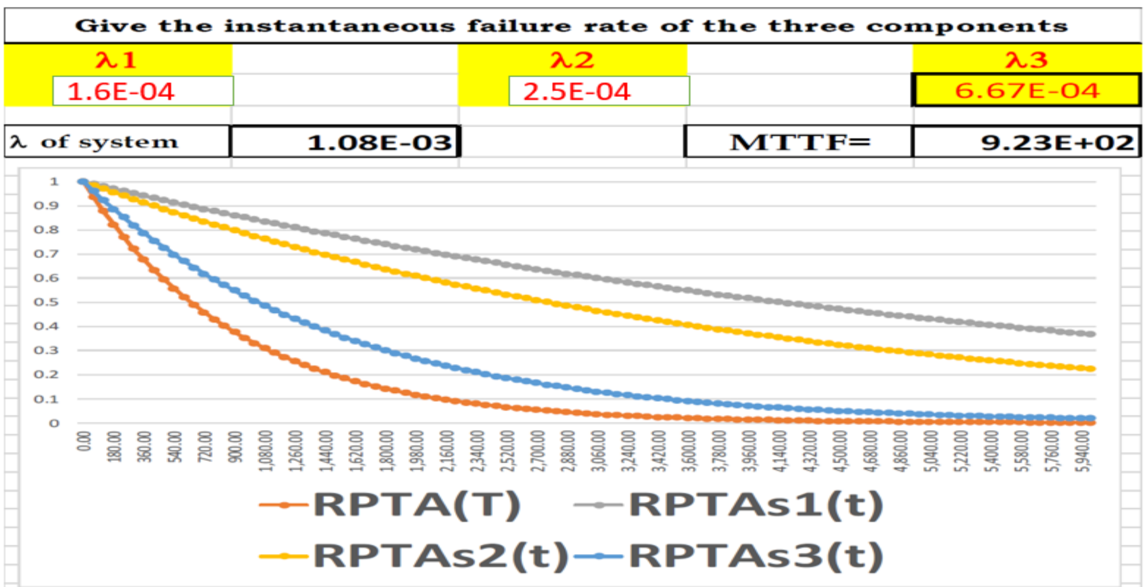

Figure 30: Reliability and the MTTF of PTA system and PTA components

From Figure 30 it can be seen that the MTTF is very low, which is due to the number of breakdowns registered. In order to improve that, the maintenance schedule needs to be adjusted.

CHAPTER 5 - CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The main objective of the study was to assess the level of resilience of operations in the Reduction department at Mozal Aluminium Company and, based on the results, to propose improvement actions through the use of risk management methods. The resilience of Reduction operations was analyzed based on calculation of PTA downtime and production late work recover. The results of the study showed that despite the numerous breakdowns and downtime, the production process is resilient, with an estimated recovery time of 16 hours. It is important to note, however, that the resilience indicated here is the result of the redoubled efforts of the work teams involved in the different shifts to fix breakdowns and eliminate late work, a situation that jeopardizes the health and safety of workers due to the high stress they are subjected to in order to meet the targets of the sector in particular and of the company in general.

The scenario described above gives a clear indication that there is a need for the company to introduce actions or improvements in its production process maintenance plan, with emphasis on preventive maintenance and installing early warnings in PTAs. These actions will not only relieve workers' stress but will also increase the company's productivity and resilience of operations.

5.2. Recommendations

- Mozal must redouble preventive maintenance actions;
- The company must develop a monitoring tool that can detect functional anomalies of the system and then make recommendations for corrections or interventions before a failure occurs or before efficiency is reduced to a low level and this can be done by installing early warnings in PTAs.

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