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RELIABILITY AND RISK EVALUATION TO DETERMINE OPTIMUM EQUIPMENT CRITICALITY CLASSIFICATION

BY

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ABSTRACT

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Title: Reliability And Risk Evaluation To Determine Optimum Equipment Criticality Classification

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Maintenance activities are common and are carried out across all types of fields and industries. The concept of maintenance has undergone multiple changes throughout the past decades due to the increased variety of physical assets and the increasing equipment and complexity to maintain that equipment. Reliability Centered Maintenance (RCM) is one of the maintenance techniques used to improve assets' reliability. In order to define maintenance strategies to maintain the equipment, the criticality of all equipment needs to be defined to understand how important the equipment is to the business. This research aims to Develop an Integrated method to derive optimum Critical Equipment Lists based on Reliability, Risks, and Cost. This will help define an optimized and efficient management maintenance plan for the organizations in different types of fields and industries. The methods used in this research will be utilizing an integration of methods including Failure Mode and Effects Criticality Analysis (FMECA), Analytic Hierarchy Process (AHP), and Optimization technique to optimize the results based on Reliability, Risks, and Costs. The integrated method results were compared with two major oil and gas companies equipment criticalities, and the integrated method results achieved a balance of equipment

criticality and were very comparable with current practices used in both major companies. The integrated method achieved balanced results, which were neither too conservative nor too lenient equipment criticalities. The balanced equipment criticalities produced from the method after optimization will help the organizations save on maintenance costs and focus the organization resources and workforce on critical items and reduce the resources spent on less critical items.

DEDICATION

I would like to dedicate this work to my parents, my friends, and every person who supported me through my master's program journey.

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I would like to thank and appreciate my thesis supervisor Dr. Galal M Abdella, for his guidance, support, and follow-up during the writing and completion of this research. I would also like to thank everyone who contributed to this research for their valuable inputs and expertise shared, which helped contribute to a new method to support the Reliability Centered Maintenance body of knowledge.

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CHAPTER 1: INTRODUCTION

1.1. Background

Maintenance activities are considered one of the most common activities in all sorts of fields, ranging from regular household items maintenance to industry-specific equipment maintenance. The concept of maintenance has undergone multiple changes throughout the past decades due to the increased physical assets in the world. Those assets include a variety of different types of buildings, plants, and equipment. Further to the increased number and variety of the equipment and plants, the complexity of that equipment and plants have also kept increasing year after year, and they must also be maintained accordingly. As such new maintenance techniques were introduced, and the understanding of maintenance and reliability has kept improving considerably with time. One of the leading frameworks used to maintain the equipment is Reliability Centered Maintenance (RCM), which is a "systematic and structured process to develop efficient and effective maintenance strategies for an asset or system to ensure safety, system functionality, mission compliance, and to minimize the probability of failure" (Gulati & Smith, 2009). Maintenance has undergone three main generations of changes; Reliability Centered Maintenance (RCM) was the third generation's main change and foundation. The first generation of maintenance mainly dealt with fixing the equipment and assets once they are broken down. The second generation of maintenance focused on lowering equipment costs, extending equipment life, and achieving higher plant availability. The third generation of maintenance where RCM was introduced, focused mainly on achieving higher plant availability and reliability, achieving more excellent safety and minimizing damages to the environment, achieving a better quality product with best cost efficiencies, and extending equipment life. (Moubray, 1999)

With each maintenance change generation, new maintenance techniques are introduced to tackle the equipment and assets' increased complexity. New methods and research are dedicated to defining equipment criticalities for the plants to focus all the maintenance efforts and resources in. To determine an equipment criticality is to understand how important that piece of equipment is to the business (Márquez, 2007). In order to determine the criticality of the equipment, the consequence of the failure of the equipment must be understood for all types of equipment. The evaluation of the consequences is company and organization-specific as each organization has different contexts for their equipment along with the consequences of failures associated with them. The final classification and prioritization of equipment criticality for maintenance will be mainly from the consequence of failure for the related equipment. One of the foremost common reliability methods used to determine the priority for maintenance items is Failure Mode and Effect Analysis (FMEA) and its extension Failure Mode, Effects and Criticality Analysis (FMECA); some authors consider those methods as one of the main essential parts for having management maintenance strategies (Aven, 2016,).

1.2. Research Aims & Objectives

This research aims to develop an integrated method to derive optimum critical equipment lists based on reliability, risks, and cost. This will help define an optimized and efficient management maintenance plan for the organizations in different types of fields and industries. The main objectives of this research are the following:

1. Analyzing existing Risk Evaluation methods used to calculate equipment criticality.
2. Identify relevant input factors that contribute to and affect the criticality of equipment.

3. Identify and analyze analytical methods to be used in the final integrated method to derive the optimum critical equipment list.
4. Identify and analyze optimization methods to be used in the final integrated method to derive the optimum critical equipment list.
5. Develop an integrated method based on identified analytical methods, risk evaluation methods, and optimization methods to derive optimum Critical Equipment Lists and maintenance plans based on reliability, costs, and risks.
6. Evaluate integrated method results with sample practices used in the oil & gas industry.

1.3. Research Scope

This research's main focus was to design and develop an integrated method to derive optimum critical equipment lists and Maintenance Plans based on reliability, risks, and costs. The method used in this research will be utilizing an integration of methods including Failure Mode and Effects Criticality Analysis (FMECA), Analytic Hierarchy Process (AHP), and optimization using Linear Programming (LP). The proposed method is limited only to calculating the criticality of the equipment's based on the inputs provided from three main factors: 1) Factors related to the equipment, 2) Factors related to the type of process that the industry is in, and 3) Management Factors related to the organization. The inputs will be assessed based on the integrated method and applied to a sample list of equipment used in the oil and gas industry. Below figure 1 shows a summarized scope for the research:

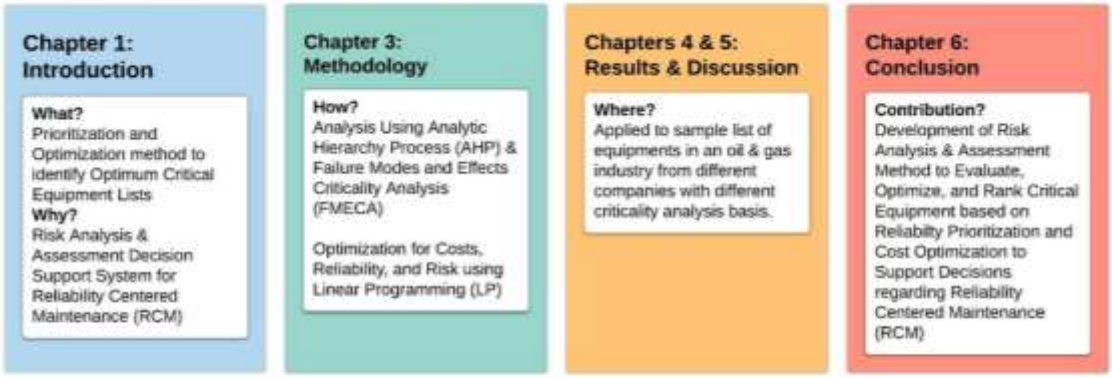

Figure 1: Scope of the Research

1.4. Research Methodology

The research will attempt to identify optimal critical equipment list and maintenance plans based mainly on reliability while considering significant factors like costs and risk in the evaluation process. The methodology will be divided into four main parts, first is inputs, then two cycles of processes, and finally, the outputs. The inputs will identify factors in three main categories: 1) Management Factors, 2) Process Factors, 3) Equipment Factors. Those factors will be fed into the first cycle of a process to prioritize the factors using Analytic Hierarchy Process (AHP) as a weighting method, and Failure Mode and Effects Criticality Analysis (FEMCA) as a risk evaluation method. The results from the first cycle of the process will be fed into the second cycle of the process, which will optimize the results based on costs and reliability using Linear Programming (LP) method. Finally, the outputs of the second process cycle will give an optimized critical equipment list based on prioritization and optimization techniques for reliability, risk, and costs. The detailed methodology will be discussed in Chapter 3: Methodology. An overview of the research methodology is presented in figure 7.

1.5. Thesis Outline

The research is divided into six main chapters. Chapter 1 will provide a general introduction to the research topic and present the research scope, objectives, and problem. Chapter 2 will explain the literature review and introduce important topics and concepts necessary for the research. Chapter 3 will discuss the methodology used in this research and explain each part of the methodology, along with data collection details and assumptions used in the research. Chapter 4 will show the details and tables of the integrated method's results to derive the optimum equipment criticality list. Chapter 5 will discuss the results obtained, compare the results with two oil & gas companies' equipment, and discuss the advantages and limitations of the method results compared to established companies' practices. Chapter 6 will provide conclusions and future work.

CHAPTER 2: LITERATURE REVIEW

The literature review chapter is divided into four sections. The first section will introduce Failure Mode and Effect Analysis (FMEA) and explain the main method concepts. The second section will explain what risk is and how risk is being evaluated in the industry. The third section will explain the general maintenance strategies being practiced in the industry. The fourth section will discuss recent literature review papers on Failure Mode and Effect Analysis (FMEA).

2.1 Introduction Into FMEA

2.1.1 Origins of FMEA

FMEA was developed by the U.S military in the 1940s and presented a strategy for identifying potential failures in the design, assembly, or manufacturing processes. Their frustrations with military weapons motivated them to develop a technique deployed to eliminate all possible root cause failures. The new method was developed and tested and was successful; thus, it was adopted by the aerospace and nuclear industry. Mikulak, McDermott, and Beauregard (2017) denote that the first formal FMEAs were carried out in the aerospace industry during the mid-1960s, whereby NASA attributed the success of the moon landing to the deployment of FMEA. Later in the 1970s, Ford Motor Company adopted the technique to solve the Ford Pinto failure, where the company successfully implemented the technique in their design process. Additionally, more companies were deploying FMEA as a tool for risk assessment, and in the year 1993, the Automotive Industry Action Group (AIAG) incorporated the technique into the QS9000 standards for the manufacture of automotive (Mikulak, McDermott & Beauregard, 2017).

Although FMEA targeted the automotive sector, other industries that demand high-reliability levels, such as the oil and gas sector, have also adopted the technique. This reliability standard has extended to most goods and even electronic products.

FMEA has evolved to include analyzing the criticality of the failure to the end-users leading to the emergence of Failure Modes and Effects and Criticality Analysis (FMECA).

2.1.2 Concept of FMEA

Historically, the earlier a failure is discovered, the less it will impact the process or product. FMEA is one of the most critical tools enabling the discovery of failure at the earliest possible time. "Mikulak, McDermott, and Beauregard (2017) define FMEA as a systematic method for identifying and preventing product and process problems before their occurrence." The technique focuses on averting defects, enhancing safety, and increasing the level of customer satisfaction. Notably, FMEA is implemented in the product design or during process development, even though conducting FMEA on existing products and processes can lead to significant benefits. Although engineers and designers have always analyzed processes and products for possible failures, the FMEA process brought a standard approach and set a common language deployed in various companies. It can also be deployed by both technical and non-technical employees at all levels. Failure modes are ways in which a system, process, or product can fail while the effects represent the outcome of this failure, which may lead to defects, waste, or harmful outcomes for the end-user. FMEA is highly effective in identifying and correcting process failure early to avert costly consequences of poor performance (Stamatis, 2003).

There exist two major classifications of FMEA, first is Process FMEA and the second is Design FMEA. Process FMEA (PFMEA) evaluates failures that impact the quality of products or those that lower the process's reliability, leading to safety hazards or customer dissatisfaction. These can include human factors, materials factors, machine factors, or environmental factors, among others. On the other hand, Design

FMEA (DFMEA) analyzes product failure probability due to reduced product life and safety or malfunction. Such concerns originate from properties of the materials deployed, tolerances, geometry, engineering noise, or interfaces with other systems or components, among others (Bluvband & Grabov, 2009).

2.1.3 FMEA & FMECA

FMEA incorporates some techniques deployed to evaluate risks associated with a product, process, machine, or system. During this analysis, the FMEA team sorts the risks from the highest to the lowest based on risk priority number, which accounts for the likelihood of failure, risk severity, and corrective action effectiveness. FMEA ranks each failure based on risk impact and the occurrence probability. This quantitative assessment is deployed both at the design and control stages.

FMECA takes this assessment a step further, whereby each failure mode is assigned to a criticality or severity level. FMECA not only identify but also investigates possible failure modes and their causes. It is a bottom-up or a top-down method of assessing risks. This technique is data-driven and links elements of a failure such as failure mode, effects of failure, and causes or mechanisms. FMECA analyzes risks measured based on criticality, which is a product of probability and severity of the risks. "FMEA and FMECA are closely related where each tool resolves to identify failure modes that may cause the failure of a process or a product. FMEA is qualitative and explores what-if-scenarios, while FMECA includes a degree of qualitative inputs (Rausand, 2004)." FMECA is derived by creating the FMEA and later performing the analysis.

FMECA should be initiated at the early stages, especially in the design process, to have the most significant impact on equipment reliability. FMECA leads to tangible design and development, operational, and cost benefits (Rausand, 2004).

2.1.4 Risk Priority Number (RPN)

As denoted earlier, the FMEA team sorts the risks based on Risk Priority Number (RPN). According to Sellappan, Nagarajan, and Palanikumar (2015), this is the risk measure applied to identify the critical failure modes associated with a design or a process. It ranges from 1, representing the best case and 1000 representing the worst case. The RPN is determined based on the severity, occurrence, and detection of the failure; see the equation below:

$$RPN = Severity \times Occurrence \times Detection$$

The severity of the failure mode is determined by giving a numerical estimate of its effect in the event it happens. It is estimated in a range of 1 to 10 with the higher the range, the higher the severity risk. The occurrence determines the likelihood of the failure mode occurring in the design life or the production process. It is also rated from 1 to 10, and the higher the number, the more the failure mode occurrence potential. Detection represents the effectiveness of identifying and preventing failure from occurring. Similarly, it is measured on a scale of 1 to 10, and the higher the number, the low the detection capabilities (Sellappan, Nagarajan, & Palanikumar, 2015). Below figures 2 to 4 will represent the details and description for each of the ten rankings according to FMEA Standard J1739:

Effect	Criteria: Severity of the Effect	Ranking
Hazardous - without warning	Very high severity ranking when a potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation without warning.	10
Hazardous - with warning	Very high severity ranking when a potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation with warning.	9
Very High	Vehicle / item inoperable, with loss of primary function.	8
High	Vehicle / item operable, but at reduced level of performance. Customer dissatisfied.	7
Moderate	Vehicle / item operable, but Comfort/Convenience item(s) inoperable. Customer experiences discomfort.	6
Low	Vehicle / item operable, but Comfort/Convenience item(s) operable at reduced level of performance. Customer experiences some dissatisfaction.	5
Very Low	Fit & Finish/Squeak & Rattle item does not conform. Defect noticed by most customers.	4
Minor	Fit & Finish/Squeak & Rattle item does not conform. Defect noticed by average customer.	3
Very Minor	Fit & Finish/Squeak & Rattle item does not conform. Defect noticed by discriminating customer.	2
None	No Effect.	1

Figure 2: Severity Ranking based on FMEA Standard J1739

Probability of Failure	Possible Failure Rates	Ranking
Very High: Failure is almost inevitable	>= 1 in 2	10
	1 in 3	9
High: Repeated failures	1 in 8	8
	1 in 20	7
Moderate: Occasional failures	1 in 80	6
	1 in 400	5
	1 in 2,000	4
Low: Relatively few failures	1 in 15,000	3
	1 in 150,000	2
Remote: Failure is unlikely.	<= 1 in 1,500,000	1

Figure 3: Occurrence Ranking based on FMEA Standard J1739

Detection	Criteria: Likelihood of Detection by Design Control	Ranking
Absolute Uncertainty	Design Control will not and/or can not detect a potential cause/mechanism and subsequent failure mode; or there is no Design Control.	10
Very Remote	Very remote chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	9
Remote	Remote chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	8
Very Low	Very low chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	7
Low	Low chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	6
Moderate	Moderate chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	5
Moderately High	Moderately high chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	4
High	High chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	3
Very High	Very high chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	2
Almost Certain	Design Control will almost certainly detect a potential cause/mechanism and subsequent failure mode.	1

Figure 4: Detection Ranking based on FMEA Standard J1739

RPN facilitate the prioritization of the high-risk issues and determine the requirement of the corrective action from the highest to the lowest RPN. In FMEA, the RPN threshold guides in determining the failure modes that need corrective action and which risks are at an acceptable level (Liu, Deng & Jiang, 2017). Due to the competing needs for resources, only significant RPN are considered for collecting the failure modes. However, using an RPN threshold exposes the customer to a degree of danger, and all failure modes are not corrected. The main challenge of using the RPN is that high RPN failure modes do not necessarily indicate a high risk for the product or process. Additionally, two failure modes with similar RPN values may not always have the same risk level.

2.1.5 Advantages and Disadvantages of FMEA

The main advantage of FMEA is its high effectiveness in evaluating services, processes, and products. This facilitates the identification of potential failure modes and determines their cause. It gives the designer an indication of the most common failure that required critical analysis (Dai et al., 2011). As a result, FMEA identifies areas that need improvement and guides the development of new processes. This is important in identifying how performance can be improved in the underperforming business segment. FMEA gives a logical and structured way of establishing concerns in operations at a minimal cost and time. It involves assessing the entire process, thus increasing the knowledge of operating processes. This is important as it can establish single failure points and system interface problems that limit success and negatively influence safety. It determines the countermeasures to eliminate the cause of the failure mode.

On the other hand, FMEA also has some limitations. The technique is a tiresome process that is time-consuming, especially while tracing the failure through the FMEA charts. According to Dai et al. (2011), FMEA is often applied late and does not influence the design and process's decision-making. Therefore, it cannot eliminate possible failure modes. FMEA disregards the relationship between different failure components and attributes that can influence failure modes. It is dependent on the subjective analysis made by a few experts, thus reliant on their skill, experience, and judgment. As a result, it is significantly unknown and unmanaged at the organizational level. Lastly, FMEA prioritizes failure modes according to their risk as a result; not all failure modes are addressed.

2.2 Risk Evaluation & Risk Matrix

As one of the aims of this thesis is to develop a method based on reduced risks, it is essential to define risk and how the risks are evaluated. The risk matrix will then be explained along with its elements and how it is used in the industry. Risk and risk elements will be defined in the below section:

- *Risk:* Is the probability that a person, property, or equipment may be harmed or damaged if exposed to hazard. In qualitative terms, the risk is the probability multiplied by consequence. (Risk, n.d.)
- *Probability (likelihood):* Is the likelihood that a specific occurrence to take place. (Probability, n.d.)
- *Consequence (Severity):* Is the result, effect, or an impact occurring, usually an unpleasant event or an accident. (Consequence, n.d.)
- *Risk Matrix:* It is a matrix that defines the risk by considering both the Probability of an event and the consequence/ outcome of the event. The matrix is used mainly during the risk assessment process and is a helpful tool for decision making. (Talbot, 2018)

A risk matrix is a tool that helps in the evaluation and prioritization of risk. There are two dimensions in a risk matrix; the first dimension is the probability (or likelihood) of an event to happen; this dimension is usually measured as a number of occurrences per year. The other dimension in a risk matrix is the consequence (or severity) of an event to happen, this dimension is usually divided into categories, and each category has a consequence description; the most common consequence categories are financial consequences, reputation consequences, environmental consequences, and safety consequences (Talbot, 2018). Multiple forms and dimensions of risk matrixes exist, there is a 3x3 risk matrix, 4x4 risk matrix, and the most common type is a 5x5 risk matrix. Below is a sample of a 5x5 risk matrix:

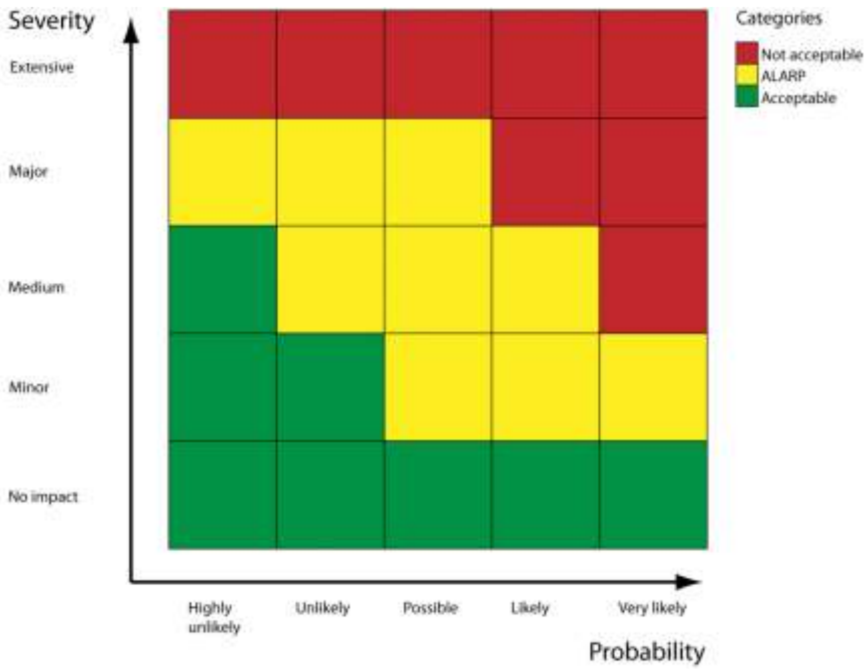

Figure 5: Sample 5x5 Risk Matrix

The risk assessment results are presented and distributed in the risk matrix; in general, the highest risk items are presented in the top right-hand corner, while the low-risk items are presented in the lower left-hand corner. The risk matrix can be balanced (symmetrical) or unbalanced (unsymmetrical). The risk matrix also contains risk categories assigned to the boxes on the risk matrix (Talbot, 2018). Below is a general description of risk categories in a risk matrix:

- *High-Risk Category (Generally Red Color):* This category is in the top right-hand corner of the risk matrix and indicates a high probability and high consequence risk. This risk is not acceptable, and control measures need to be in place to reduce the risk to acceptable limits (Talbot, 2018).
- *Low-Risk Category (Generally Green Color):* This category is on the lower left-hand side of the risk matrix and indicates low probability and low consequence risk. If any equipment falls under this category, then maintenance plans can be relaxed as the items are low risk (Talbot, 2018).
- *Medium Risk Category (Generally Yellow Color):* This category is in the middle of the risk matrix and between the high-risk category and the low-risk category. Equipment's in this category needs to be monitored and controlled. The control should be As Low As Reasonably Practicable (ALARP) (Talbot, 2018).

2.3 Maintenance Strategies Used in Reliability Centered Maintenance (RCM)

Reliability centered maintenance (RCM) "is a systematic and structured process to develop an efficient and effective maintenance strategy for an asset or system to ensure safety, system functionality, mission compliance, and to minimize the probability of failure" (Gulati & Smith, 2009). RCM is designed into assets and equipment attributes that help minimize maintenance needs by using reliability components that are easy to repair. There are four general types of maintenance strategies used in RCM, which include: Corrective Maintenance (CM), Preventative Maintenance (PM), Condition-Based Maintenance (CBM), and Risk-Based

Maintenance (RBM) strategies. Each maintenance type will be defined below, and the main differences of each type will be explained in table one below:

- *Corrective Maintenance (CM):* are maintenance activities and repair actions initiated as a direct result from the observed condition of an asset after functional failure or measured condition before functional failure. (Gulati & Smith, 2009)
- *Preventative Maintenance (PM):* is a maintenance strategy based on recent inspection, component replacement, and overhauling of the equipment at the planned interval, regardless of its condition at the time of maintenance. (Gulati & Smith, 2009)
- *Condition-Based Maintenance (CBM):* is a maintenance activity required based on the current condition and health of the equipment or asset, as determined from inspections or measurements taken from the monitoring of equipment health/condition. (Gulati & Smith, 2009)
- *Risk-Based Maintenance (RBM):* is a maintenance activity that is carried out based on the most risk-sensitive assets or systems. In this maintenance strategy, the most efficient and economical way is determined that optimize the resources distribution to achieve minimum risks and repairs. (Gulati & Smith, 2009)

Each maintenance strategy has its strengths and weaknesses, as such a combination of maintenance strategies is used in the industry based on the final risks identified for the equipment and the risk tolerance that the company management is willing to accept for failures. Below table one will show a simple comparison between corrective, preventative, condition-based, and risk-based inspection and maintenance approaches in four areas: 1) the strategy of each approach, 2) the scope of each approach, 3) the main benefit of each approach, 4) the main issues of each approach.

Table 1: Maintenance and Inspection Approaches

	Corrective	**Preventative**	**Condition-Based**	**Risk-Based**
Strategy	Run to Fail	Focus on Regulations	Equipment Life	Risk Management
Scope	Critical Equipment	Everything you are aware of	Unit cycle limiting equipment	Anything needed to operate at acceptable risk
Benefits	Reduced Budget	Leveled Scope	Run-length assurance	Reduced Risk & Scope, improved Availability
Issues	Costly Failures, Uncertainty	Costly Failures, Increased Budget	Costly Decisions	Cultural Change

As shown in table one above, each maintenance approach has its benefits suitable for certain equipment and systems. The most optimum combination of maintenance strategies will need to be selected based on the equipment's final criticality and the acceptable risk level approved by the organization management. Finding the correct equipment criticality levels and classifications is needed to select the most suitable maintenance strategy for any given organization.

2.4 Additional Papers Reviewed for FMEA:

In this section, only the top three highly related FMEA concepts reviewed in the papers will be critically evaluated and explained below.

According to (Santos, Silva, Ramos, Campilho, & Ferreira, 2019), the authors developed a method to classify equipment criticality based on the importance of the final product's equipment. The paper assumed only three-level of criticalities: A, B, and C. Some of the factors used for evaluation in this method were: Technological

Complexities, Costs, Quality, Availability, and Safety & Environment. The method was applied in four different food factories in Portugal, including a cookies factory, Semolina Factory, and two Pasta Factories. Below is the methodology used for criticality classification of the food industry in the research paper:

Figure 6: Stages of the methodology used for the criticality assignment process

As the classification only assumed three criticality levels, the maintenance strategies that were suggested to be applied were also linked to the three groups assigned. Therefore, the application of Reliability Centered Maintenance (RCM) and Preventative Maintenance Plans and Corrective Maintenance Plans are ideal for this approach as each maintenance strategy will fall under one category of the three assigned criticality levels. The method used in the paper was developed considering multi-disciplinary teams consisted of personnel from different departments, including the maintenance team, quality, and safety team, along with the production team. The evaluation criteria used were based mainly on Quality, Availability, Safety, Cost, and Technological Complexity. Three classification levels were used where classification level one was the most severe and level three being the lowest in severity. Each element was thoroughly explored and defined, then applied to the four food companies to identify equipment criticality. The results showed a reduction of working hours on maintenance activities after applying the method across a period of half a year. However, the benefits gained and decreased in the percentage of the failures after applying this method were minimal and observed only at 0.73%.

Also, in the case study paper by (Carpitella, Certa, Izquierdo, & La Fata, 2018), the authors present a new method to optimize a complex system; the method used combines reliability analysis and multi-criteria decision making (MCDM) to optimize maintenance activities. The method incorporates Failure Mode, effects, and criticality analysis (FMECA) as an initial process; then, the fuzzy TOPSIS method is applied as a second method to rank failure modes previously identified. The authors introduced three evaluation methods for prioritization of failure modes, those three evaluation criteria are 1) operational time taken to perform maintenance activities after the occurrence of the failure mode, 2) the way of execution of said maintenance activities on the failure mode, 3) the frequency of occurrence of said failure globally/ internationally. Analytic Hierarchy Process (AHP) was also used to weight the evaluation criteria of the applied method in this case study, and a group of experts was consulted to provide their inputs to finalize the criteria's weights. The case study results showed the application of the method on a street cleaning vehicle and suggested performing both corrective and preventative maintenance actions based on the results obtained.

In another case study paper (Melani, Murad, Caminada Netto, Souza, & Nabeta, 2018), the authors present a model to identify the most critical components of a system to contribute to the prioritization of maintenance activities. The authors propose a combination of methods, including Hazard and Operability Study (HAZOP), Fault Tree Analysis (FTA), Failure Mode, and Effects Criticality Analysis (FMECA), and Analytic Network Process (ANP). The method was applied to a coal-fired power plant on the flue gas desulfurization system. The method starts with a systematic study where available trees and block diagrams will be created. The second part is system risk and reliability analysis, where HAZOP, FTA, and FMECA are being evaluated. The third part is criticality analysis and ranking, where ANP will be used based on equipment criticality considerations. The method was applied to a coal-fired power plant, and the results were identified to match the most critical failures observed in the power plant. The method results were compared with data gathered over a couple of years, and most results were found satisfactory, which shows the soundness of the method used and the careful steps considered building the process. However, only a small improvement of the technique is required on the process, which is to reduce the variation percentage of the results as observed from the sensitivity analysis.

This research paper will contribute to the body of knowledge by developing an integrated risk assessment method to evaluate, optimize, and rank critical equipment based on reliability prioritization and cost optimization to support Reliability Centered Maintenance (RCM) decisions.

CHAPTER 3: METHODOLOGY

Chapter 3 will explain the detailed methodology of the integrated method, and each section of the inputs, process, and outputs will be explained. This section will discuss research methodology overview and the four main sections of the methodology, Data Collection and the sources of the data collected, Data Analysis explaining how the data will be analyzed and the process in which the data will go through, and finally the assumptions made for this methodology in order to function optimally.

3.1 Research Methodology Overview

The developed integrated method to derive optimum critical equipment lists was developed considering three key elements: Reliability as a priority, Risk as a second priority, and Cost as a third priority. The methodology is divided into four sections; the first section is for the inputs and identification of critical factors to input into the model. Then the inputs go through two cycles of processes; Process-1 is to prioritize all factors identified using two established methods: 1) Analytic Hierarchy Process (AHP) as a screening tool as well as weighting method to be used in the next steps, 2) Failure Mode and Effects Criticality Analysis (FMECA), which is a tool to identify potential failure modes in a system and investigate the effects such failures might cause to the said system. Process-2 will happen next, where all data will be fed into an optimization process using Linear Programming (LP) with goals to maximize reliability and minimize both costs and risks. The outputs will provide optimized criticality equipment lists based on reliability, risks, and costs. Figure 7 below shows the summarized methodology for this research paper:

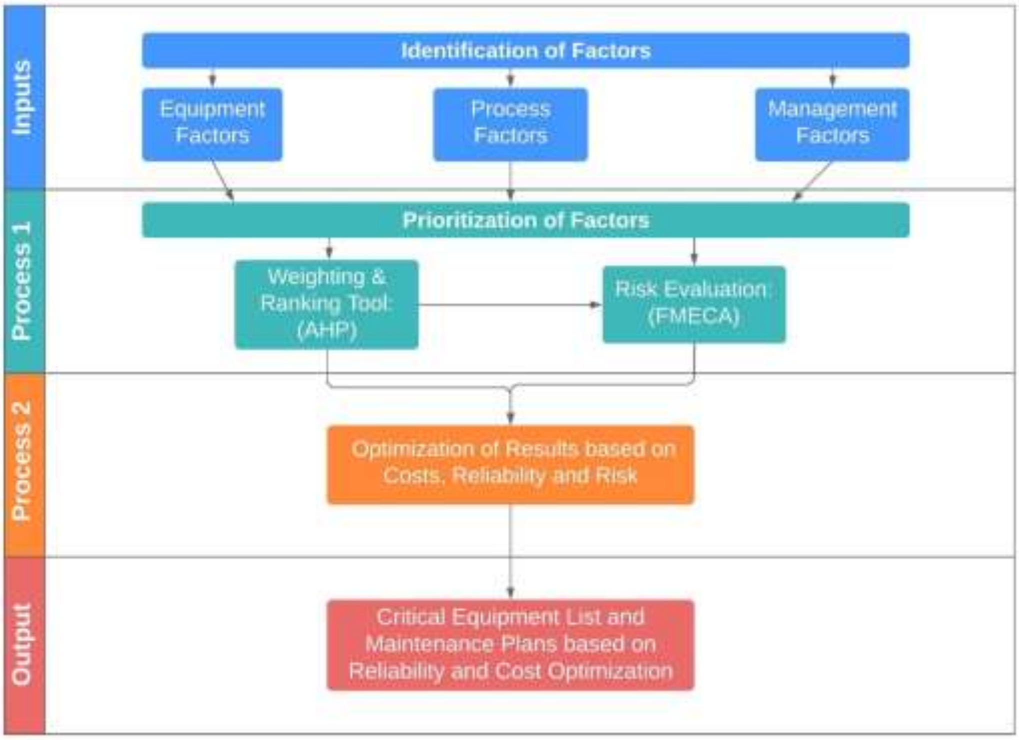

Figure 7: Research Methodology Overview

In part below, the steps under each section of the methodology will be explained along with their details:

3.1.1 Methodology Section 1- Inputs:

The first section of the methodology handles the inputs into the integrated method. In this section, identifying key factors will take place in three main categories: 1) Equipment Factors, 2) Process Factors, 3) Management Factors. Each factor will be explained in this section and describe each factor input's relevance and importance to the integrated methodology process and outputs.

3.1.1.1 Equipment Factors:

The equipment factors described in this section refer to all the necessary factors required in order to be able to assess equipment criticality. They are mainly defined to satisfy the two processes used in the methodology: Failure Mode and Effects Criticality Analysis (FMECA) and Analytic Hierarchy Process (AHP). The factors used are the most common details that are required to perform the analysis. Below is a list of factors used for consideration regarding the criteria for equipment:

Table 2: Equipment Criticality Criteria Considerations

Severity	Occurrence	Detection
Environmental Impact	Toxic Impacts	Fire and Explosion Impact
Personnel Impact	Business Costs	Availability
Efficiency	Quality	Equipment Datasheets
Operating Philosophy	Maintenance Manuals	Vendor Catalog
Pressure	Temperature	Thickness
Fluid/Medium	PFD	P&ID

3.1.1.2 Process Factors:

Process factors refer to the different types of manufacturing processing commonly used in the industry. Each manufacturing process will have unique operating conditions that will affect the final product's nature and urgency. Process factors will be considered only if the organization use a combination of processes to deliver their end product. A weighted factor will be used to support a criticality assessment based on expert judgment inputs from the survey. Process factor contribution will be counted as zero if the manufacturing process does not change while producing the end product. Below is a brief description of each manufacturing process (Goldense, 2015):

- *Repetitive Process:* is a manufacturing process where a production line produces the same product of items all year long, with minimum setup requirement or changeover. The production speed can be increased or decreased to meet customer demands (Goldense, 2015).
- *Discrete Process:* is a manufacturing process that utilized the production line where the process is diverse, with multiple setups and changeover frequencies. That is mainly due to differences in products in the production line that necessitate the changes, which lead to more production time (Goldense, 2015).

- *Job Shop:* is a manufacturing process that utilizes production areas instead of production lines. This type of manufacturing focuses more on custom products and usually are either made-to-order (MTO) or made-to-stock (MTS) (Goldense, 2015).
- *Process-Continuous:* is a manufacturing process that is similar to the repetitive process and run all year long. The main difference between repetitive and continuous production is the production in a continuous process: gases, liquids, slurries, or powders (Goldense, 2015).
- *Process-Batch:* is a manufacturing process that is similar to a job shop and discrete processes. One batch or multiple batches can be produced depending on customer demands; once the demand is met, the equipment is cleaned and ready to produce the next batch (Goldense, 2015).

3.1.1.3: Management Factors:

Management factors refer to the strategic organizational goals and targets of the assessee company. For example, a company with a reliability target of 99.9% will require a massive amount of resources from the workforce, cost, and time to achieve the target percentage. In contrast, a reliability target of 95% or 90% will require fewer resources and reduce overall maintenance costs and business impacts from failures. The targets generally are linked to the type of business the company is in; for example, in the aircrafts industry, a compromise of 0.1% in reliability will lead to catastrophic consequences as human lives will be lost. However, for other types of businesses like the manufacturing of capacitors, the failure's impact is only financial consequences, and failure of components in this type of business can be relaxed depending on the organizational goals and targets. The targets will be used during the optimization phase in process 2 of the methodology, where linear programming will be used. The targets will need to be assigned from the input phase of the methodology.

3.1.2 Methodology Section 2- Process 1:

The second section of the methodology analyzes all inputs from the first section utilizing two main methods: Failure Mode and Effect Criticality Analysis (FMECA) and Analytic Hierarchy Process (AHP):

3.1.2.1 Failure Mode and Effect Criticality Analysis (FMECA):

As explained in the literature review section, FMECA evaluates risks using Risk Priority Number (RPN), which is a risk measure applied that helps identify critical failure modes in the design of a process. The RPN has a range from 1 to 1000 and contains three main elements Severity, Occurrence, and Detection. Each element ranges from 1 to 10. The detailed description of each range can be found from FMEA Standard J1739 in figures 2 to 4. The Risk Priority Number equation is shown below:

$$RPN = Severity \times Occurrence \times Detection$$

3.1.2.2 Analytic Hierarchy Process (AHP):

Analytic Hierarchy Process is a method used for analyzing and organizing complex decisions. AHP has three main elements: 1) the goal that the problem is trying to solve, 2) the alternatives which are the possible solutions to the problem, 3) the criteria that the final decision will be based on. Below, figure 8 will show the general AHP structure, and figure 9 will define the pairwise comparison scale used in AHP:

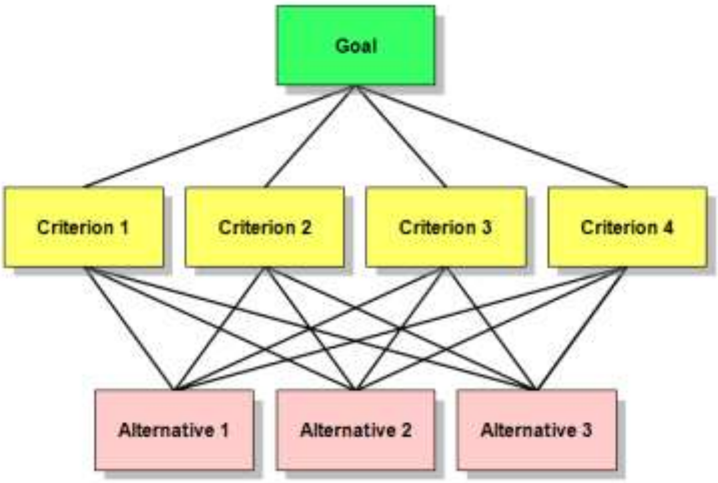

Figure 8: General AHP Structure

The Fundamental Scale for Pairwise Comparisons		
Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
Intensities of 2, 4, 6, and 8 can be used to express intermediate values. Intensities 1.1, 1.2, 1.3, etc. can be used for elements that are very close in importance.		

Figure 9: AHP Pairwise Comparison Scale

AHP allows for both qualitative and quantitative criteria to be evaluated, allowing the technique to be used flexibly, depending on the inputs. In this research, AHP will assign both weightage and prioritization to the factors defined in the input stage. The weights will be assigned from survey results based on experts' inputs and experience in the related field. The calculations will be shown in chapter four, the results section, and will also be discussed in chapter five.

3.1.3 Methodology Section 3- Process 2:

The first section of the methodology helps in identifying the risk of equipment using FMECA and RPN. The results from RPN will provide risk ranking, which can help in the final assessment. However, RPN results will be from a subjective perspective, and the results will be qualitative. Therefore process two is introduced to add and evaluate quantitative measures missed from the qualitative approach, namely the approximate reliability data for each equipment, the approximate direct and indirect costs of the equipment, and the risk details for safety, namely toxic impact, environmental impacts, fire and explosion impact, and personnel impact. Each of those criteria will be inputted in the second process, and an optimization process will be applied to rearrange the initial priority ranking of the equipment from RPN, adding a qualitative assessment to optimize the final results. The optimization targets will be taken from management inputs, process inputs, and management inputs, and the weights will be derived using AHP and will be applied to the optimization method.

The objective function for the optimization was mainly based on the criteria of reliability, risk and cost. The objective function for reliability was to maximize reliability, while for both the risks and the costs, the objective function was to minimize risks and costs. The optimization details and description are mentioned in chapter four the results section.

3.1.4 Methodology Section 4- Outputs:

The integrated method's outputs will be a critical equipment list based on reliability, cost, and risks. Four criticality categories will be assigned: A, B, C, and D, where A being the highest criticality and D being the lowest criticality or run to fail. The initial list of equipment will list all the assessed equipment after completing the first process after being analyzed from AHP and FMECA methodology; the list will then be optimized in the second process after inputting the results into an optimization technique evaluate the data using a quantitative approach. The list will be rearranged after optimization for reliability, risk, and costs. The final list will include an equipment list qualitatively assessed using FMECA and quantitively optimized using quantitative details of reliability, risk, and costs.

3.2 Data Collection

In this research, data were collected from two major companies in the oil & gas industry. The data consists of details of different types of equipment used in their process plants. The data include details of equipment criticality, equipment probability, and equipment consequence. Sample equipment types include:

- *Boilers:* is an equipment where fluids are being heated; in industrial plants, boilers are generally used to generate steam to be used as a heating or cooling medium in the plant. In this research, an example of a Steam Boiler will be used to analyze the results section's criticality analysis.
- *Columns:* is equipment where two or more components are being separated from a mixture by using the difference in boiling points of the components being separated. In this research, an example of the Sulfinol Absorber column will be used to analyze the results section's criticality analysis.
- *Filters:* are equipment mainly used to remove or block any small particle or other items that have been slipped or already existing in the system to stop them from damaging any further equipment down-stream of the equipment. In this research, an example of a Fuel Gas filter will be used to analyze the results section's criticality analysis.
- *Flares:* flares in industrial plants are used to burn excess gases that are released from safety devices, usually PRVs, in order to protect the system or equipment

from over pressurization. In this research, an example of Jetty Flare (which flares Hydrocarbon) will be used to analyze the results section's criticality analysis.

- *Furnaces:* is the equipment used to increase the fluid or medium temperature to achieve a certain function or process reaction. In this research, an example of a Reaction furnace will be used to analyze the results section's criticality analysis.
- *Heat Exchangers:* is equipment built for efficient heat transfer from one medium to another medium. In this research, an example of an Air Finned heat exchanger will be used for the criticality analysis in the results section.
- *Loading Arms:* is the equipment used to transport gases or liquids from one location to another, usually from one tank to another. In this research, an example of a Liquified Natural Gas loading arm will be used for the criticality analysis in the results section.
- *Piping:* is simply a set of pipes used to transport fluids from one location to another; the fluids can be gasses, liquids, or a mixture of both. In this research, two examples of pipes will be used for the criticality analysis in the results section, the first is a clean service type of piping, and the second will be a dirty/corrosive service type of piping.
- *Pressure Relive Devices:* is equipment designed to protect a system or equipment from over-pressurization. The device will relieve the extra pressure to protect the equipment from a different type of damages like rupture or fire. In this research, an example of PRV in a corrosive service will be used to analyze the results section's criticality analysis.

- *Pressure Vessels:* is simply equipment designed to withstand external and internal pressures. In this research, an example of a Molecular Sieve Bed Pressure Vessel will be used for the criticality analysis in the results section.
- *Storage Tanks:* are containers designed to store gases or liquids for short-term or long-term usages as applicable. In this research, an example of a Fresh Cooling Water storage tank will be used for the criticality analysis in the results section.

A Survey was created and circulated to industry experts, mainly in the oil and gas industry. The survey questionnaire is listed in appendix 4. Due to the data collected's confidentiality and sensitivity, the data will be censored, and only representative equipment will be used for research purposes.

Data will be collected for reliability, risk, and costs to determine the final criticality ranking. Overall Equipment Effectiveness (OEE) is a tool used to measure reliability and evaluate how efficient and productive a manufacturing operation is. OEE measures three factors: 1) Availability is the measure of planned and unplanned stoppage times (Run time / planned production time), 2) Efficiency (or Performance) is how efficient the equipment run without slowdowns or brief stops in production, and 3) Quality refers to how many parts manufactured that do not meet the quality standards of the product (Trout, 2019). Below figure 10 shows the global OEE benchmark, which will also be used in the analysis in this thesis:

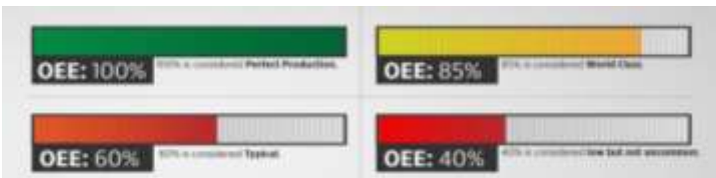

Figure 10: Overall Equipment Effectiveness Benchmark (Trout, 2019)

3.3 Data Analysis

This section will explain how the data will be evaluated in the results section. This section will provide information on how the data will be evaluated and the basis for the evaluation and choosing the final outputs. As the focus of this thesis is to provide a ranking for the criticality of equipment, this section will provide more information on the analysis part to determine the criticality's final ranking. A total of four criticality rankings will be used, and they are described in table 3 below:

Table 3: Equipment Criticality Ranking Guidelines

Criticality Ranking		**Description**
A	Safety-Critical (High Critical Equipment)	● Those are equipment that can prevent or cause events that are serious threats to personnel and the environment. ● This Ranking will be used for *Safety-Critical* Equipment in a High-Risk Category zone (Red and orange zone in risk matrix) ● High Critical Equipment have a risk ranking between 32 to 64 in the risk matrix
B	Business Critical (High Critical Equipment)	● Those are equipment that can prevent, or cause, a serious business impact described in both financial and production loss. ● This Ranking will be used for *Financial Critical* Equipment in a High-Risk Category zone (Red and orange zone in risk matrix) ● High Critical Equipment have a risk ranking between 32 to 64 in the risk matrix
C	Essential Critical (Medium Critical Equipment)	● Those are equipment that results in a lower business impact in terms of financial or production losses. ● This Ranking will be used for Essential Critical Equipment, usually Medium Risk Category zone (Yellow zone in risk matrix) ● Medium Critical Equipment have a risk ranking between 8 to 24 in the risk matrix
D	Run to Fail (Low Critical Equipment)	● Those are equipment that has no impact on both business nor performance. They can also be described as equipment where their reactive maintenance cost is less than their scheduled maintenance costs. ● This Ranking will be used for Run-To-Fail equipment’s, Usually in the Low-Risk Category zone (Green to White zone in risk matrix) ● Low Critical Equipment has a risk ranking between 1 to 6 in the risk matrix.

The final results of the criticality ranking used in the thesis will be divided into four criticalities according to the description provided in the table above. Both A and B Critical equipment falls under High-Risk Category zones; the distinction between them is to differentiate safety-critical equipment from business and critical financial equipment. This distinction is needed to know the safety-critical equipment and plan their maintenance plans and approvals accordingly. Below figures 11 and 12 will show the equipment criticality risk matrix used in this thesis, along with a sample flowchart showing the criticality assessment after risk evaluation:

Consequence		**Probability**				
		E (Extremely Improbable)	**D (Very Improbable)**	**C (Improbable)**	**B (Somewhat Probable)**	**A (Probable)**
Major	**5**	8	16	32	48	64
Serious	**4**	6	12	24	36	48
Moderate	**3**	4	8	16	24	32
Minor	**2**	2	4	8	12	16
Slight	**1**	1	2	4	6	8

Figure 11: Equipment Criticality Assessment Risk Matrix

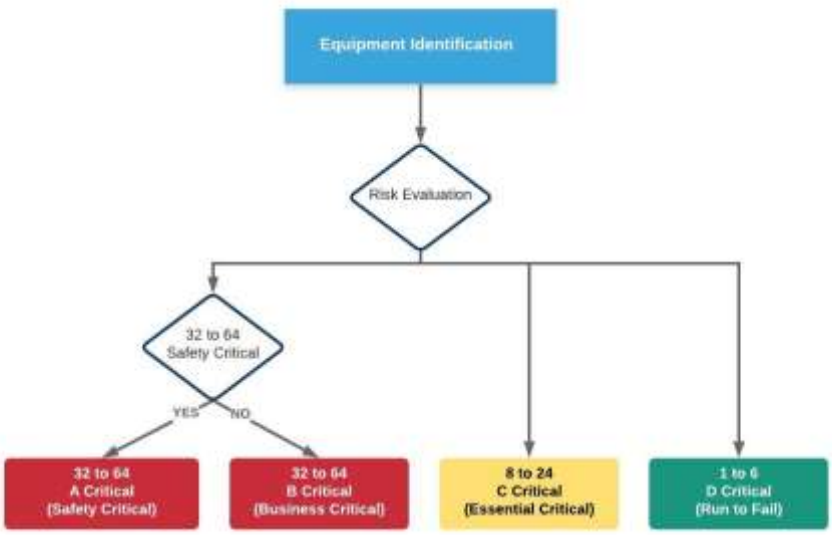

Figure 12: Equipment Criticality Assessment after evaluation

3.4 Assumptions

Numerous assumptions have been made during the development of the integrated method. Below is a list of the assumptions made:

- All methods will be used for the sole purpose/functionality of finding the criticality of the equipment.
- Only four levels of criticality will be used: A, B, C, and D.
- The highest criticality level (A) will be used and distinguished for safety risks; this criterion can be changed depending on the business/industry being assessed. For this thesis, Criticality Level A will be used for safety risks as per Table 3 descriptions.
- Four maintenance plans are discussed: Corrective Maintenance, Preventative Maintenance, Condition Based Maintenance, and Risk-Based Maintenance.
- Survey Results will be used for the inputs of Equipment Factors.
- Specific Scenarios will be used for each type of equipment; the final criticality assignment will be based on personnel's experience answering the survey.
- OEE will be used as a tool to measure reliability.
- Survey Results will be used for the inputs for Process Factors.
- All manufacturing processes used are evaluated based on the experience of personnel answering the survey.
- Survey Results will be used for the inputs for Management Factors.

CHAPTER 4: RESULTS

This section will list all the results to derive the optimum equipment criticality list method. This section will include all the equations used along with all the tables and figures to reach the final results. All the steps in the results will be discussed in Chapter 5: Discussion.

The results will evaluate different types of 12 types of equipment; the inputs are received from a survey circulated to professionals working in the industry, mainly in the oil and gas industry. Each equipment has a different scenario to distinguish the importance of the equipment in the process. Survey questions, along with the scenario used, can be found in Appendix 4. For each equipment, a three-letter shortcut will be used to optimize the space for the evaluation tables. The equipments are: 1) Boiler [Boi], 2) Column [Col], 3) Filter [Fil], 4) Flare [Fla], 5) Furnace [Fur], 6) Heat Exchanger [Hex], 7) Loading Arm [LoA], 8) Pipe scenario 1 [Pip1], 9) Pipe scenario 2 [Pip2], 10) Pressure Relive Device/Valve [PRV], 11) Pressure Vessel [PV], 12) Storage Tank [ST].

Equipment Factors Results:

Risk Priority Number (RPN) evaluation:

Table 4: Results of RPN Evaluation

Equipment	Severity	Occurrence	Detection	RPN	S*O
Boi	7.6	4.2	6.1	194.71	31.92
Col	6.3	4.4	6.8	188.50	27.72
Fil	1.1	7.1	1.9	14.84	7.81
Fla	8.1	6.3	4.8	244.94	51.03
Fur	7.5	5.2	7.4	288.60	39.00
HEx	4.2	5.1	4.3	92.11	21.42
LoA	8.3	6.6	3.2	175.30	54.78
Pip1	4.6	5.5	3.7	93.61	25.30
Pip2	8.8	6.4	4.2	236.54	56.32
PRV	8.9	6	5	267.00	53.40
PV	6.7	5.9	3.4	134.40	39.53
ST	6.4	4.3	4.9	134.85	27.52

Analytic Hagiarchy Process (AHP) Evaluation:

Table 5: Equipment Factors AHP Criteria Ranking Results

	Criteria Ranking – Equipment Factors				**Priority Vector**	
Criteria	Toxic Impacts	Env. Impact	Fire & Exp. Impact	Perso. Impact	**Criteria**	**x**
Toxic Impacts	1	2.5	1.5	0.333	Toxic Impacts	0.252
Env. Impact	0.400	1	0.667	0.286	Env. Impact	0.105
Fire & Exp. Impact	0.667	1.5	1	0.400	Fire and Explosion Impact	0.162
Perso. Impact	3	3.5	2.5	1	Personnel Impact	0.482

Table 6: Calculation of Consistency Ratio for Equipment Factors

Criteria	**A**				**x**	**Ax**
Toxic Impacts	1.000	2.500	1.500	0.333	0.252	0.917
Env. Impact	0.400	1.000	0.667	0.286	0.105	0.451
Fire & Explosion Impact	0.667	1.500	1.000	0.400	0.162	0.679
Personnel Impact	3.000	3.500	2.500	1.000	0.482	2.008

Table 7: Calculation of Consistency Index

Consistency Index Calculation				
n	**λ**	**CI**	**Index of cons. (Table)**	**CR**
4	4.079	0.026	0.90	0.029

Table 8: AHP Evaluation for Equipment Factors of Toxic Impacts

Alternatives Ranking (Toxic Impacts) – Equipment Factors													**x**
Tox. Imp.	**Boi**	**Col**	**Fil**	**Fla**	**Fur**	**HE x**	**Lo A**	**Pip 1**	**Pip 2**	**PRV**	**PV**	**ST**	**Tox. Imp.**
Boi	1.0	0.5	2.6	0.6	0.9	0.8	0.7	1.2	0.5	0.5	0.7	1.1	0.06
Col	1.9	1.0	5.1	1.1	1.7	1.5	1.4	2.3	1.0	1.0	1.3	2.1	0.12
Fil	0.4	0.2	1.0	0.2	0.3	0.3	0.3	0.5	0.2	0.2	0.3	0.4	0.02
Fla	1.8	0.9	4.6	1.0	1.5	1.4	1.3	2.1	0.9	0.9	1.2	1.9	0.11
Fur	1.2	0.6	3.1	0.7	1.0	0.9	0.8	1.4	0.6	0.6	0.8	1.3	0.07
HEx	1.3	0.7	3.4	0.7	1.1	1.0	0.9	1.5	0.6	0.7	0.9	1.4	0.08
LoA	1.4	0.7	3.7	0.8	1.2	1.1	1.0	1.7	0.7	0.7	0.9	1.5	0.09
Pip1	0.8	0.4	2.2	0.5	0.7	0.6	0.6	1.0	0.4	0.4	0.6	0.9	0.05
Pip2	2.0	1.0	5.3	1.1	1.7	1.5	1.4	2.4	1.0	1.0	1.3	2.2	0.12
PRV	2.0	1.0	5.2	1.1	1.7	1.5	1.4	2.4	1.0	1.0	1.3	2.1	0.12
PV	1.5	0.8	4.0	0.9	1.3	1.2	1.1	1.8	0.8	0.8	1.0	1.6	0.09
ST	0.9	0.5	2.4	0.5	0.8	0.7	0.7	1.1	0.5	0.5	0.6	1.0	0.06

Table 9: AHP Evaluation for Equipment Factors of Environmental Impact

Alternatives Ranking (Environmental Impact) – Equipment Factors													**x**
Tox. Imp.	**Boi**	**Col**	**Fil**	**Fla**	**Fur**	**HE x**	**Lo A**	**Pip 1**	**Pip 2**	**PRV**	**PV**	**ST**	**Env. Imp.**
Boi	1.0	0.8	2.5	0.6	0.9	1.6	0.6	1.2	0.7	1.2	0.7	0.7	0.07
Col	1.2	1.0	3.1	0.7	1.1	1.9	0.8	1.4	0.9	1.4	0.9	0.8	0.09
Fil	0.4	0.3	1.0	0.2	0.4	0.6	0.3	0.5	0.3	0.5	0.3	0.3	0.03
Fla	1.7	1.4	4.3	1.0	1.6	2.6	1.1	2.0	1.2	2.0	1.2	1.2	0.13
Fur	1.1	0.9	2.8	0.6	1.0	1.7	0.7	1.3	0.8	1.3	0.8	0.8	0.08
HEx	0.6	0.5	1.6	0.4	0.6	1.0	0.4	0.7	0.5	0.7	0.5	0.4	0.05
LoA	1.6	1.3	4.0	0.9	1.4	2.5	1.0	1.8	1.1	1.8	1.2	1.1	0.12
Pip1	0.9	0.7	2.2	0.5	0.8	1.4	0.5	1.0	0.6	1.0	0.6	0.6	0.06
Pip2	1.4	1.2	3.6	0.8	1.3	2.2	0.9	1.6	1.0	1.6	1.0	1.0	0.10
PRV	0.9	0.7	2.2	0.5	0.8	1.4	0.5	1.0	0.6	1.0	0.6	0.6	0.06
PV	1.4	1.1	3.5	0.8	1.3	2.1	0.9	1.6	1.0	1.6	1.0	0.9	0.10
ST	1.5	1.2	3.7	0.9	1.3	2.3	0.9	1.7	1.0	1.7	1.1	1.0	0.12

Table 10: AHP Evaluation for Equipment Factors Fire & Explosion Impact

Alternatives Ranking (Fire and Explosion Impact) – Equipment Factors													x Fir& Exp.
Tox. Imp.	**Boi**	**Col**	**Fil**	**Fla**	**Fur**	**HEx**	**LoA**	**Pip1**	**Pip2**	**PRV**	**PV**	**ST**	
Boi	1.0	1.3	7.1	1.5	1.1	1.8	1.2	1.3	1.1	1.0	1.6	2.1	0.12
Col	0.8	1.0	5.7	1.2	0.9	1.4	0.9	1.1	0.9	0.8	1.3	1.7	0.09
Fil	0.1	0.2	1.0	0.2	0.2	0.3	0.2	0.2	0.2	0.1	0.2	0.3	0.02
Fla	0.7	0.8	4.8	1.0	0.8	1.2	0.8	0.9	0.7	0.7	1.1	1.4	0.08
Fur	0.9	1.1	6.3	1.3	1.0	1.6	1.0	1.2	1.0	0.9	1.4	1.8	0.10
HEx	0.6	0.7	4.0	0.8	0.6	1.0	0.7	0.8	0.6	0.6	0.9	1.2	0.07
LoA	0.8	1.1	6.0	1.3	1.0	1.5	1.0	1.1	0.9	0.8	1.3	1.8	0.10
Pip1	0.7	0.9	5.3	1.1	0.8	1.3	0.9	1.0	0.8	0.7	1.2	1.5	0.09
Pip2	0.9	1.1	6.5	1.4	1.0	1.6	1.1	1.2	1.0	0.9	1.4	1.9	0.11
PRV	1.0	1.3	7.2	1.5	1.1	1.8	1.2	1.4	1.1	1.0	1.6	2.1	0.12
PV	0.6	0.8	4.5	0.9	0.7	1.1	0.8	0.9	0.7	0.6	1.0	1.3	0.07
ST	0.5	0.6	3.4	0.7	0.5	0.9	0.6	0.7	0.5	0.5	0.8	1.0	0.06

Table 11: AHP Evaluation for Equipment Factors Personnel Impact

Alternatives Ranking (Personnel Impact) – Equipment Factors													x Per. Imp.
Tox. Imp.	**Boi**	**Col**	**Fil**	**Fla**	**Fur**	**HEx**	**LoA**	**Pip1**	**Pip2**	**PRV**	**PV**	**ST**	
Boi	1.0	1.3	3.5	1.1	1.2	1.3	1.1	1.2	1.2	1.1	1.3	2.3	0.11
Col	0.8	1.0	2.7	0.9	0.9	1.0	0.8	1.0	0.9	0.8	1.0	1.8	0.08
Fil	0.3	0.4	1.0	0.3	0.3	0.4	0.3	0.4	0.3	0.3	0.4	0.7	0.03
Fla	0.9	1.2	3.1	1.0	1.0	1.2	1.0	1.1	1.1	1.0	1.2	2.1	0.10
Fur	0.9	1.1	3.0	1.0	1.0	1.1	0.9	1.0	1.0	0.9	1.1	2.0	0.09
HEx	0.8	1.0	2.6	0.8	0.9	1.0	0.8	0.9	0.9	0.8	1.0	1.7	0.08
LoA	0.9	1.2	3.2	1.0	1.1	1.2	1.0	1.1	1.1	1.0	1.2	2.1	0.10
Pip1	0.8	1.1	2.8	0.9	1.0	1.1	0.9	1.0	1.0	0.9	1.1	1.9	0.09
Pip2	0.8	1.1	2.9	0.9	1.0	1.1	0.9	1.0	1.0	0.9	1.1	1.9	0.09
PRV	0.9	1.2	3.2	1.0	1.1	1.2	1.0	1.1	1.1	1.0	1.2	2.2	0.10
PV	0.8	1.0	2.7	0.9	0.9	1.0	0.8	1.0	0.9	0.8	1.0	1.8	0.08
ST	0.4	0.6	1.5	0.5	0.5	0.6	0.5	0.5	0.5	0.5	0.6	1.0	0.05

Table 12: Final Ranking of Alternatives with Weights of Equipment

	Ranking Of Alternatives				x	Altern. Weights
	Toxic Impacts	**Env. Impact**	**Fire & Exp. Impact**	**Personnel Impact**		
Boi	0.062	0.073	0.115	0.108	0.252	0.094
Col	0.120	0.090	0.092	0.084	0.105	0.095
Fil	0.023	0.029	0.016	0.031	0.162	0.027
Fla	0.109	0.125	0.077	0.096	0.482	0.099
Fur	0.072	0.080	0.102	0.092		0.087
HEx	0.080	0.047	0.065	0.081		0.075
LoA	0.087	0.116	0.097	0.099		0.098
Pip1	0.052	0.064	0.085	0.088		0.076
Pip2	0.124	0.104	0.106	0.091		0.103
PRV	0.122	0.064	0.116	0.101		0.105
PV	0.094	0.101	0.073	0.084		0.086
ST	0.057	0.107	0.056	0.047		0.057

Table 13: Reliability Inputs for each equipment to be used in quantitative optimization

Reliability Inputs				
Equipment	**Availability**	**Efficiency**	**Quality (Yield)**	**OEE**
Boiler	98.7%	95.5%	96.1%	90.58%
Column	96.8%	97.9%	96.7%	91.64%
Filter	93.5%	91.3%	94.9%	81.01%
Flare	97.2%	98.8%	98.3%	94.40%
Furnace	97.9%	96.7%	96.4%	91.26%
Heat Exchanger	94.8%	95.7%	97.4%	88.36%
Loading Arm	98.1%	97.9%	99.3%	95.37%
Piping 1	97.9%	94.7%	98.7%	91.51%
Piping 2	98.2%	96.8%	99.1%	94.20%
Pressure Relive Device	98.7%	97.1%	99.4%	95.26%
Pressure Vessel	98.5%	98.1%	97.1%	93.83%
Storage Tank	98.9%	98.7%	98.5%	96.15%

Table 14: Business Impact Results

Equipment	Business Impact
Boilers	2.3
Columns	1.8
Filters	5.0
Flares	2.0
Furnaces	2.5
Heat Exchangers	4.0
Loading Arms	1.0
Piping 1	2.7
Piping 2	1.6
Pressure Relive Devices	1.9
Pressure Vessels	1.7
Storage Tanks	3.0

Table 15: Business Impact Description

Business Impact Level	Description ($)
1	More than 10,000,000
2	1,000,000 – 10,000,000
3	100,000 – 1,000,000
4	10,000 – 100,000
5	Less than 10,000

Process Factors Results:

Analytic Hagiarchy Process (AHP) Evaluation:

Table 16: Process Factors AHP Criteria Ranking Results

	Criteria Ranking – Process Factors			**Priority Vector**	
Criteria	Cost	Reliability	Risk	**Criteria**	x
Cost	1	0.333	0.5	Cost	0.164
Reliability	3	1	2	Reliability	0.539
Risk	2	0.5	1	Risk	0.297

Table 17: Calculation of Consistency Ratio for Process Factors

Criteria	**A**			**x**	**Ax**
Cost	1	0.333	0.5	0.164	0.492
Reliability	3	1	2	0.539	1.625
Risk	2	0.5	1	0.297	0.894

Table 18: Consistency Index Calculation for Process Factors

Consistency Index Calculation				
n	**λ**	**CI**	**Index of cons. (Table)**	**CR**
3	3.009	0.005	0.58	0.008

Table 19: AHP Evaluation for Process Factors Cost Criteria 1

	Alternatives Ranking – Process Factors 1			**x (Cost)**
Cost	Repetitive	Discrete	Job-Shop	
Repetitive	1	3	5	0.633
Discrete	0.333	1	3	0.260
Job-Shop	0.2	0.333	1	0.106

Table 20: AHP Evaluation for Process Factors Reliability Criteria 1

	Alternatives Ranking – Process Factors 1			**x (Reliability)**
Reliability	Repetitive	Discrete	Job-Shop	
Repetitive	1	2	4	0.571
Discrete	0.5	1	2	0.286
Job-Shop	0.25	0.5	1	0.143

Table 21: AHP Evaluation for Process Factors Risk Criteria 1

	Alternatives Ranking – Process Factors 1			**x (Risk)**
Risk	Repetitive	Discrete	Job-Shop	
Repetitive	1	0.5	0.333	0.164
Discrete	2	1	0.5	0.297
Job-Shop	3	2	1	0.539

Table 22: Final Ranking of Alternatives with Weights of Manufacturing Process 1

	Ranking Of Alternatives 1			**x**	**Altern. Weights**
	Cost	**Reliability**	**Risk**		
Repetitive	0.633	0.571	0.164	0.164	0.460
Discrete	0.260	0.286	0.297	0.539	0.285
Job-Shop	0.106	0.143	0.539	0.297	0.255

Table 23: AHP Evaluation for Process Factors Cost Criteria 2

	Alternatives Ranking – Process Factors 2		**x (Cost)**
Cost	Process-Continuous	Process-Batch	
Process-Continuous	1	3	0.750
Process-Batch	0.333	1	0.250

Table 24: AHP Evaluation for Process Factors Reliability Criteria 2

	Alternatives Ranking – Process Factors 2		**x (Reliability)**
Reliability	Process-Continuous	Process-Batch	
Process-Continuous	1	2	0.667
Process-Batch	0.5	1	0.333

Table 25: AHP Evaluation for Process Factors Risk Criteria 2

	Alternatives Ranking – Process Factors 2		**x (Risk)**
Risk	Process-Continuous	Process-Batch	
Process-Continuous	1	0.5	0.333
Process-Batch	2	1	0.667

Table 26: Final Ranking of Alternatives with Weights of Manufacturing Process 2

	Ranking Of Alternatives 2			**x**	**Altern. Weights**
	Cost	**Reliability**	**Risk**		
Process-Continuous	0.633	0.571	0.164	0.164	0.581
Process-Batch	0.260	0.286	0.297	0.539	0.419
				0.297	

Management Factors Results:

Below are management factor inputs from the survey which will be used in the optimization process as targets:

Table 27: Management Factors Results

Availability	99.6%	**Cost**	Level 2
Efficiency	97.5%	**Risk**	Medium / Yellow
Quality	99.2%	**OEE**	World Class

Optimization Description:

Below are optimization description and results:

In general terms, the objective function is either to minimize or maximize and follows below general formula:

$$\min\ (/or)\ max \qquad z = \sum_{j=1}^{n} c_j x_j$$

Subject to (constrains and decision variables):

$$\sum_{j=1}^{n} a_{ij} x_j \ \le b_i \ \ , i = 1,2, . . , m$$

$$x_j \ \ge 0 \ , j = 1,2. . , n$$

Below is list of List of variables used in optimization along with their description:

Table 28: List of Variables in Optimization

Variable	Description
$Eq_{i\ ,TSI}$	Toxic (Safety Risk) Impacts Equipment Variable
TSI_T	Toxic (Safety Risk) Impacts Target
$Eq_{i\ ,ESI}$	Environmental (Safety Risk) Impact Equipment Variable
ESI_T	Environmental (Safety Risk) Impact Target
$Eq_{i\ ,F\&ESI}$	Fire and Explosion (Safety Risk) Impact Equipment Variable
$F\&ESI_T$	Fire and Explosion (Safety Risk) Impact Target
$Eq_{i\ ,PSI}$	Personnel (Safety Risk) Impact Equipment Variable
PSI_T	Personnel (Safety Risk) Impact Target
$Eq_{i\ ,BI}$	Business (Cost) Impact Equipment Variable
BI_T	Business (Cost) Impact Target
$Eq_{i\ ,R}$	Reliability (In terms of OEE) Equipment Variable
R_T	Reliability (In terms of OEE) Target
$Eq_{i\ ,MP}$	Manufacturing Process (Repetitive, Discrete, Job-Shop, Process-Continuous, Process-Batch) Equipment Variable
MP_T	Manufacturing Process (Repetitive, Discrete, Job-Shop, Process-Continuous, Process-Batch) Target

The equipment variables are the 12-equipment selected in the research which are : 1) Boiler [Boi], 2) Column [Col], 3) Filter [Fil], 4) Flare [Fla], 5) Furnace [Fur], 6) Heat Exchanger [Hex], 7) Loading Arm [LoA], 8) Pipe scenario 1 [Pip1], 9) Pipe scenario 2 [Pip2], 10) Pressure Relive Device/Valve [PRV], 11) Pressure Vessel [PV], 12) Storage Tank [ST]. The targets are taken from management factors, process factors, and AHP equipment factors.

The objective functions used for various targets:

$$(Safety\ Risk)\ \ min \qquad z_1 = \sum_{i=1}^{12} Eq_{i\ ,TSI} + \sum_{i=1}^{12} Eq_{i\ ,ESI} + \sum_{i=1}^{12} Eq_{i\ ,F\&ESI} + \sum_{i=1}^{12} Eq_{i\ ,PSI}$$

$$(Cost)\ \ min \qquad z_2 = \sum_{i=1}^{12} Eq_{i\ ,BI}$$

$$(Reliability)\ \ max \qquad z_3 = \sum_{i=1}^{12} Eq_{i\ ,R}$$

$$(Manufacturing\ Process)\ \ max \qquad z_4 = \sum_{i=1}^{12} Eq_{i\ ,MP}$$

Subject to:

$Toxic\ (Safety)\ Impact$:	$Eq_{i\ ,TSI} \leq\ TSI_T$
$Enviromental\ (Safety)\ Impact$:	$Eq_{i\ ,ESI} \leq\ ESI_T$
$Fire\ \&\ Explosion\ (Safety)\ Impact$:	$Eq_{i\ ,F\&ESI} \leq\ F\&ESI_T$
$Personnel\ (Safety)\ Impact$:	$Eq_{i\ ,PSI} \leq\ PSI_T$
$Business\ (Cost)\ Impact$:	$Eq_{i\ ,BI} \leq\ BI_T$
$Reliability$:	$Eq_{i\ ,R} \geq\ R_T$
$Manufacturing\ Process$:	$Eq_{i\ ,MP} \geq\ MP_T$
$All\ Variables$:	$Eq_i\ \geq\ 0$

Optimization Results and Method Comparison:

Below are optimization results after utilizing quantitative inputs from Risks, Reliability, and Costs to optimize equipment criticality list, along with comparison results:

Table 29: Criticality Results & Method Comparison

Equipment	Integrated Method	Company A	Company B
Boiler	B	S (B)	B
Column	C	S (C)	B
Filter	C	C	C
Flare	A	S (A)	A
Furnace	B	S (B)	B
Heat Exchanger	C	S (C)	C
Loading Arm	B	B	B
Piping 1	B	S (C)	B
Piping 2	B	S (B)	B
Pressure Relive Device	A	A	A
Pressure Vessel	B	S (C)	B
Storage Tank	C	S (C)	B

Table 30: Criticality Results & Method Comparison by Criticality Ranking

Criticality	Integrated Method	Company A	Company B
A	Flare Pressure Relive Device	Flare Pressure Relive Device	Flare Pressure Relive Device
B	Boiler Furnace Loading Arm Piping 1 Piping 2 Pressure Vessel	Boiler Furnace Piping 2	Boiler Column Furnace Loading Arm Piping 1 Piping 2 Pressure Vessel Storage Tank
C	Column Filter Heat Exchanger Storage Tank	Column Filter Heat Exchanger Piping 1 Pressure Vessel Storage Tank	Filter Heat Exchanger
D	-	-	-

CHAPTER 5: DISCUSSION

This chapter will discuss the integrated method results and compare them with similar samples of equipment from two major oil & gas companies. The inputs were gathered from experts' support in the industry, mainly from the oil & gas industry. 12 sample equipment was selected to apply the integrated method to derive optimum criticality equipment list. Each equipment was defined with a specific scenario in order to be able to define the equipment criticality in a specific context. For example, heat exchangers will be evaluated differently if they contain different fluid mediums. The fluid will introduce different damage mechanisms that might cause the equipment to have different damage mechanisms, and the failure of the equipment with the specific service will have a different consequence on the company.

After getting all the inputs from experts using the survey, FMECA was used to evaluate the RPN inputs. RPN calculates the risk of the equipment using three parameters, Severity (or consequence), Occurrence (or Probability), and Detection (or Effectiveness). Table 4 in chapter 4 shows the results of using RPN. Two outputs were calculated; first is RPN, which is Severity x Occurrence x Detection; the second is Severity x Occurrence. In the first calculation where SxOxD is used, the results would be from a scale of 1 to 1000. Usually, the calculation is acceptable after defining the threshold for each criticality level. For example, an RPN value of more than 210 is designated Criticality A, between 120 to 210, as Criticality B. However, this approach was debated since the calculations include three factors of equal weights, namely Severity, Occurrence, and Detection. However, it was debated that the three factors do not have equal weights and that the severity (consequence) and occurrence (probability) should have a higher factor since they affect the evaluation results more than the detection method of the specific failure. As such, in this thesis results, Severity x

Occurrence was calculated as they will indicate the equipment's criticality more clearly than the Severity x Occurrence x Detection (RPN) approach. To illustrate the difference, an example can be found in table 4, where for Loading Arm equipment, the Severity x Occurrence achieved a value of 54.78 (A Critical), wherein the RPN approach, since the detection factor is in place. It is relatively easier to identify the damage, the RPN value was 175.30, and the overall criticality of the equipment will be reduced to B Critical; this case illustrates that the RPN approach devalued the equipment's criticality. Another example is for the Furnace equipment, the Severity x Occurrence achieved a value of 39 (B Critical), wherein the RPN approach with Detection factor in place, the RPN value was 288.60, and the criticality of the equipment is increased to A Critical. This example illustrates that the RPN approach increased the value of the criticality of the equipment.

After finding the results of FMECA using RPN as the first process, the data will need to be optimized further since the RPN values were obtained from a qualitative approach and the results, in turn, are subjective. Therefore an optimization will be carried out for the results to introduce quantitative measures and make the results more accurate. The quantitative measures were also obtained from experts, and they are mainly in three categories 1) Reliability: where reliability data will be inputted for Availability, Efficiency, and Quality to determine reliability measure of OEE (Overall Equipment Effectiveness), the reliability results will be evaluated based on management factors inputted and the criticality list will be optimized for reliability, 2) Risk: where risk will be evaluated based on the consequences of failure mainly related to safety, four main criteria will be evaluated for safety consequences, Toxic Impacts, Environmental Impacts, Fire and Explosion Impacts, and Personnel Impacts, and 3) Costs: The direct and indirect financial impacts will be evaluated, the business impact will be divided into five levels and described in table 15.

The first step to the optimization of equipment criticality list is to determine first which factor of Reliability, Risk, or Costs have the most effect on equipment criticality, so the AHP method will be used to determine the weights of the factors, and the results are displayed in table 16, which was also used to evaluate in process factors. Starting with the risk, four criteria were used to evaluate safety consequences, which were Toxic Impacts, Environment Impacts, Fire and Explosion Impact, and Personnel Impact. Tables 5 to 12 show the results of equipment factors using the AHP technique. The weights were obtained using AHP, and the same will be used in the optimization process to derive an optimum criticality list, including a quantitative assessment of risk and FMECA risk assessment using RPN. It can be noted from table 12 that Pressure Relieve Devices scored highest and ranked first. This assessment supports RPN evaluation as PRVs are highly critical and safety devices, and this also supports being under A critical list. Piping 2 scored second-highest, as this equipment mainly affects business and financial impacts. It cannot be under A critical since this category is only for safety equipment; however, it can be under B critical as per Table 3 Guidelines. Flares scored third highest, and they are also safety equipment, so this also supports the decision for flares to be under A critical equipment list. Table 13 shows the reliability input for each equipment, and the Overall Equipment Effectiveness (OEE) reliability measure was used to measure and rank the equipment's reliability. Three factors were assessed: the Availability, Efficiency, and Quality, the multiplication of the three factors will result in OEE. Table 13 shows the results of the reliability assessment based on OEE. According to the benchmarks of OEE as shown in figure 10, most of the equipment assessed is under the World Class category, which is between 85% and 100%. Only filters achieved less than 85% and are considered as Typical effectiveness, and the same is understandable as the equipment is usually not very critical in the production and can be easily maintained with a proper maintenance program. The OEE reliability results will also be used in the optimization process. Table 14 shows the business impact results for each equipment. The business impact includes both the direct and indirect costs of failure for each equipment. The direct financial costs are the losses incurred directly to repair the failed equipment, including the materials and workforce. The indirect costs indicate the costs of lost production due to the equipment not being in service, normally indirect costs of the equipment is a lot higher than the direct costs, so the two measures were combined as total business costs instead of calculating direct and indirect costs separately. It can be noted that Loading Arm has the highest business impact for this specific case in the oil and gas industry. This is understandable as loading arms will ship the final product after completing all process changes, and quality specs, any failure in the loading arm will directly affect production and have huge financial consequences. Pressure Vessel and Column also scored high in business impact, as the equipment scenario selected is a core process to produce the final product, any failure in the equipment will result in the shutdown of the plant and cause financial consequences. Flares and PRVs are safety equipment. However, they also have huge financial consequences for failure. Both Flares and PRVs have high safety consequences and high financial consequences. Table 15 describes the business impact levels, which consist of 5 levels, the highest level of 1, reflecting that equipment failure will result in overall direct and indirect cost loss of more than 10,000,000 dollars. Level 2 reflects business costs of failure between 1,000,000 to 10,000,000 dollars, level 3 reflects business costs of failure between 100,000 and 1,000,000 dollars, level 4 reflects business costs of failure between 10,000 and 100,000 dollars, and finally, level 5 reflects business costs of failure of fewer than 10,000 dollars. The business impact scales can be adjusted to reflect different businesses if the method is applied to a different industry. The values for the five business impact levels are chosen to reflect the oil and gas industry and to be able to compare the final results of the equipment criticality list with two companies in the field. The next process factors were assessed to evaluate the different manufacturing processes used in the industry. Each process will affect the equipment's criticality decisions. The manufacturing process was also evaluated using AHP to determine suitable weights for evaluation in the optimization process (Process 2). A survey was created, and inputs were taken from experts in the field. The results of the process factors evaluation are listed in tables 16 to 26. It can be noted from table 22 that the Repetitive manufacturing process scored highest in AHP, followed by the Discrete process, and finally Job-Shop Process. It can also be noted from table 26 that the Process-Continuous manufacturing process is more important than Process-Batch based on the evaluation of risks, costs, and reliability. Table 27 shows the management factors results collected from experts in the industry. The same benchmarks will be used for evaluation and optimization of the final results of equipment criticality.

The method's final results can be found in table 29, where it is divided into three columns. Column 1 shows the results of the integrated method after optimization. Column 2 shows the equipment criticality assessment used in an oil and gas company with a similar equipment scenario as described for the inputs. Due to confidentiality, the first company will be detonated by the name Company A. Column 3 shows the equipment criticality assessment of another oil and gas company, with a similar equipment scenario as described for the inputs. Due to confidentiality, the second company will be detonated the name Company B.

The integrated method utilized four Equipment Criticality Levels (A, B, C, D), both Companies A & B also uses four equipment criticality levels (A, B, C, D), therefore the comparison of results will be on the same scale, and there is no need for extrapolation. As explained in chapter 3, part 3.3 Data analysis, the results are evaluated based on four criticality levels with descriptions defined in table 3. It is important to note that the companies used for comparison might have slight differences in guidelines for assessment. A clear example is when compared with Company A. Company A also uses criticality (S), which means Static Equipment, all equipment in this criticality are not part of regular maintenance, and specialized focal points in the company will initiate the maintenance and repair plans for this equipment. For this specific type of criticality, subject matter experts (SMEs) from Company A were requested to provide the closest equipment criticality from Criticality A to Criticality D. The reflected equipment criticality is noted between brackets in column 2. For Company B, they share similar four equipment criticality as the integrated method. However, the difference is that the company uses four levels of business impacts and consequences, while the integrated method uses five levels for business impacts. Therefore, company B's assessment method will vary slightly from the integrated method; however, the final results will align into the same four equipment criticality levels.

It can be noted that from table 30 that the integrated method shares a lot of similarities with both companies for the final criticality risk ranking of the equipment. First, for the A critical equipment, which reflects the equipment that must be maintained as they are safety-critical equipment, it is noted that all methods used in company A and B, as well as integrated method, have the same equipment results, which are the flares and pressure relive devices. For the B critical equipment, differences can be noticed between the three approaches used between the companies and the integrated method. It is noticed that company A is not very conservative in their evaluation for equipment criticality, as such only 3 equipment wherein B criticality for Company A. In contrast, Company B are very conservative in their evaluation, and it was noted that most of the equipment falls under B Criticality, specifically 8 out of 12 pieces of equipment fall under Criticality B. The integrated method achieved a balance between the two companies, and six pieces of equipment fall under the B Criticality. All equipment in criticality B for Company A are listed in the integrated method. However, not all criticality B for Company B is listed since Company B uses a more conservative analysis approach. The optimization technique helped reduce critical equipment in Criticality B and shifted them to Criticality C for the integrated method. For Equipment Criticality of C, it was noticed that Company B has the lowest number of equipment in this criticality with only two equipment.

In contrast, Company B was less conservative and had 6 out of 12 pieces of equipment in criticality C. the integrated method achieved a balance of risk and listed only four equipment in Criticality of C, all of which are aligned with Company A, however only matching with two pieces of equipment in Company B as they were more conservative. No Equipment Criticality of D was achieved using the integrated method to assess the scenarios described for each equipment. The results are matching with both Company A & B as no other company had equipment criticality of D with the scenarios described for the equipment.

The integrated method achieved a balance of equipment criticality that was not too conservative as the approach used in Company B and not too relaxed as the approach used in Company A.

The results were very comparable with current practices used in both major companies in the oil and gas field, which adds a level of confidence that the integrated method results are reliable from the analysis factors.

CHAPTER 6: CONCLUSION AND FUTURE WORK

In conclusion, this thesis contribution is related to evaluating and improving the Reliability Centered Maintenance (RCM) body of knowledge. The research proposes an Integrated method to derive optimum Critical Equipment Lists based on Reliability, Risks, and Cost. This will help define optimized and efficient management maintenance plans for organizations in different fields and industries. The method used in this research utilized an integration of methods including Failure Mode and Effects Criticality Analysis (FMECA), Analytic Hierarchy Process (AHP), and optimization using Linear Programming (LP). The proposed method is limited only to calculating the criticality of the equipment. The methodology used is divided into four sections. The first section was for the inputs and identification of critical factors to input into the model. Then two cycles of processes were used. The first Process (Process-1) was to prioritize all factors identified using two established methods: Analytic Hierarchy Process (AHP) and Failure Mode and Effects Criticality Analysis (FMECA). The second process (Process-2) was an optimization process using Linear Programming (LP) to maximize reliability and minimize both costs and risks. The results obtained from the integrated method were compared with two established oil and gas companies, the integrated method achieved a balance of equipment criticality that was not extremely conservative as the approach used in Company B, and not too relaxed as the approach used in Company A.

The optimization process used in the integrated method helped achieve a balanced equipment criticality list, which will assist the organizations in saving on maintenance costs and utilizing the organization resources on critical items and reducing the resources used on less critical items.

For future work, it is recommended that further factors are explored and integrated into the method, along with exploring other optimization techniques that could be utilized to help in adding to the body of knowledge of reliability centered maintenance.

REFERENCES

Bluvband, Z., & Grabov, P. (2009, January). Failure analysis of FMEA. In 2009 AnnualReliability and Maintainability Symposium (pp. 344-347). IEEE.

Dai, W., Maropoulos, P. G., Cheung, W. M., & Tang, X. (2011). Decision-making in product quality based on failure knowledge. International Journal of Product Lifecycle Management, 5(2-4), 143-163.

Liu, H., Deng, X., & Jiang, W. (2017). Risk evaluation in failure mode and effects analysis using fuzzy measure and fuzzy integral. Symmetry, 9(8), 162.

Mikulak, R. J., McDermott, R., & Beauregard, M. (2017). The basics of FMEA. CRC Press.

Rausand, M. (2004). System Analysis Failure Modes, Effects, and Criticality Analysis. SystemReliability Theory (2nd ed), Wiley.

Sellappan, N., Nagarajan, D., & Palanikumar, K. (2015). Evaluation of risk priority number (RPN) in design failure modes and effects analysis (DFMEA) using factor analysis. International Journal of Applied Engineering Research, 10(14), 34194-34198.

Stamatis, D. H. (2003). Failure mode and effect analysis: FMEA from theory to execution. Quality Press.

Risk. (n.d.). Retrieved June 10, 2020, from http://www.businessdictionary.com/definition/risk.html

Probability. definition and meaning. (n.d.). Retrieved June 10, 2020, from http://www.businessdictionary.com/definition/probability.html

Definition of Consequence | Dictionary.com. (n.d.). Retrieved June 10, 2020, from https://www.dictionary.com/browse/consequence

Talbot, J. (2018, July 31). What's right with risk matrices? Retrieved June 3, 2020, from https://www.juliantalbot.com/post/2018/07/31/whats-right-with-risk-matrices

Goldense, B. (2015, August 24). The 5 Types of Manufacturing Processes. Retrieved May 29, 2020, from https://www.machinedesign.com/community/contributing-technical-experts/article/21831946/the-5-types-of-manufacturing-processes

Gulati, R., & Smith, R. (2009). Maintenance and Reliability Best Practices (1st ed.). Connecticut, United States: Industrial Press, Inc.

Moubray, J. (1999). Reliability-Centred Maintenance (2nd ed.). Maarssen, Netherlands: Elsevier.

Márquez, C. A. (2007). The Maintenance Management Framework: Models and Methods for Complex Systems Maintenance (Springer Series in Reliability Engineering) (2007th ed.). Wiesbaden, Germany: Springer.

Aven, T. (2016). Supplementing quantitative risk assessments with a stage addressing the risk understanding of the decision maker. Reliability Engineering & System Safety, 152, 51–57. https://doi.org/10.1016/j.ress.2016.03.003

Trout, J. (2019, June 6). Overall Equipment Effectiveness (OEE): An Overview. Retrieved June 14, 2020, from https://www.reliableplant.com/Read/11785/overall-equipment-effectiveness

Santos, T., Silva, F. J. G., Ramos, S. F., Campilho, R. D. S. G., & Ferreira, L. P. (2019). Asset Priority Setting for Maintenance Management in the Food Industry. Procedia Manufacturing, 38, 1623–1633. https://doi.org/10.1016/j.promfg.2020.01.122

Carpitella, S., Certa, A., Izquierdo, J., & La Fata, C. M. (2018). A combined multi-criteria approach to support FMECA analyses: A real-world case. Reliability

Engineering & System Safety, 169, 394–402. https://doi.org/10.1016/j.ress.2017.09.017

Melani, A. H. A., Murad, C. A., Caminada Netto, A., Souza, G. F. M., & Nabeta, S. I. (2018). Criticality-based maintenance of a coal-fired power plant. Energy, 147, 767–781. https://doi.org/10.1016/j.energy.2018.01.048

Piasson, D., Bíscaro, A. A. P., Leão, F. B., & Mantovani, J. R. S. (2016). A new approach for reliability-centered maintenance programs in electric power distribution systems based on a multiobjective genetic algorithm. Electric Power Systems Research, 137, 41–50. https://doi.org/10.1016/j.epsr.2016.03.040

Tian, Z.-, Wang, J.-, & Zhang, H.-. (2018). An integrated approach for failure mode and effects analysis based on fuzzy best-worst, relative entropy, and VIKOR methods. Applied Soft Computing, 72, 636–646. https://doi.org/10.1016/j.asoc.2018.03.037

Oguz, E., Kubicek, M., & Clelland, D. (2018). Failure modes and criticality analysis of the preliminary design phase of the Mars Desert Research Station considering human factors. Reliability Engineering & System Safety, 178, 247–254. https://doi.org/10.1016/j.ress.2018.06.023

Gupta, G., & Mishra, R. P. (2018). Identification of Critical Components Using ANP for Implementation of Reliability Centered Maintenance. Procedia CIRP, 69, 905–909. https://doi.org/10.1016/j.procir.2017.11.122

Peeters, J. F. W., Basten, R. J. I., & Tinga, T. (2018). Improving failure analysis efficiency by combining FTA and FMEA in a recursive manner. Reliability Engineering & System Safety, 172, 36–44. https://doi.org/10.1016/j.ress.2017.11.024

Florian, M., & Sørensen, J. D. (2015). Planning of Operation & Maintenance Using Risk and Reliability Based Methods. Energy Procedia, 80, 357–364. https://doi.org/10.1016/j.egypro.2015.11.440

Vishnu, C. R., & Regikumar, V. (2016). Reliability Based Maintenance Strategy Selection in Process Plants: A Case Study. Procedia Technology, 25, 1080–1087. https://doi.org/10.1016/j.protcy.2016.08.211

Kiran, S., Prajeeth Kumar, K. P., Sreejith, B., & Muralidharan, M. (2016). Reliability Evaluation and Risk Based Maintenance in a Process Plant. Procedia Technology, 24, 576–583. https://doi.org/10.1016/j.protcy.2016.05.117

Nie, R.-, Tian, Z.-, Wang, X.-, Wang, J.-, & Wang, T.-. (2018). Risk evaluation by FMEA of supercritical water gasification system using multi-granular linguistic distribution assessment. Knowledge-Based Systems, 162, 185–201. https://doi.org/10.1016/j.knosys.2018.05.030

Fattahi, R., & Khalilzadeh, M. (2018). Risk evaluation using a novel hybrid method based on FMEA, extended MULTIMOORA, and AHP methods under fuzzy environment. Safety Science, 102, 290–300. https://doi.org/10.1016/j.ssci.2017.10.018

Bashiri, M., Badri, H., & Hejazi, T. H. (2011). Selecting optimum maintenance strategy by fuzzy interactive linear assignment method. Applied Mathematical Modelling, 35(1), 152–164. https://doi.org/10.1016/j.apm.2010.05.014

APPENDIX:

Appendix 1: List of Abbreviations:

Table 31: List of Abbreviations

Abbreviation	Definition
AHP	Analytic Hierarchy Process
ALARP	As Low As Reasonably Practicable
ANP	Analytic Network Process
BWM	Best-Worst Method
CMMS	Computerized Maintenance Management System
FMEA	Failure Mode and Effect Analysis
FMECA	Failure mode and effects criticality analysis
FTA	Fault Tree Analysis
GP	Goal Programming
GRA	Grey relational analysis
HAZOP	Hazard and Operability Study
HDA	Human Design Approach
LAM	Linear Assignment Method
MCDM	Multi-Criteria Decision Making
MTO	Made-to-Order
MTS	Made-to-Stock
OEE	Overall Equipment Effectiveness
PDCA	Plan Do Check Act
PEW	Proximity Entropy Weight
PM	Preventive Maintenance
PSA	Probabilistic Safety Assessment
RBI	Risk Based Inspection
RCM	Reliability Centered Maintenance
RE	Fuzzy Relative Entropy
RPN	Risk Priority Number
SEW	Similarity Entropy Weight
SWOT	Strength, Weakness, Opportunity, Threats Analysis

Appendix 2: Glossary of Terms

Table 32: Glossary of Terms

Term	Definition
Analytic Hierarchy Process	Is a method used for analyzing and organizing complex decisions. AHP has three main elements: 1) the goal that the problem is trying to solve, 2) the alternatives which are the possible solutions to the problem, 3) the criteria that the final decision will be based on
Condition-Based Maintenance	are maintenance activities that are required based on the current condition and health of the equipment or asset, as determined from inspections or measurements taken from the monitoring of equipment health/condition.
Consequence (Severity)	Is the result, effect, or an impact occurring, usually an unpleasant event or an accident.
Corrective Maintenance	are maintenance activities and repair actions that are initiated as a direct result from observed condition of an asset after functional failure, or measured condition before functional failure.
Detection	Is a numerical estimate of the effectiveness of the control measures applied, to detect or prevent the cause of the failure mode.
Discrete Process	is a manufacturing process that utilized the production line where the process is diverse, with multiple setups and changeover frequencies. That is mainly due to differences in products in the production line that necessitate the changes which lead to more production time.
Failure Mode and Effect Analysis	Is a technique to examine an asset, process, or design, to determine the possible ways that it can fail and it's potential effects; and afterward identify the most appropriate mitigation measures and tasks for the highest priority risk items.
Job Shop	is a manufacturing process that utilizes production areas instead of production lines. This type of manufacturing focuses more on custom products and usually are either made-to-order (MTO) or made-to-stock (MTS).
Multi-Criteria Decision Making	Is a research method that evaluates multiple criteria's against each other, usually conflicting criteria's, to arrive to the best decision among conflicting interests.
Overall Equipment Effectiveness	Is a tool used to measure reliability and is used to evaluate how efficient and productive a manufacturing operation is.
Preventative Maintenance	are maintenance strategy based on recent inspection, component replacement, and overhauling of the equipment at the planed interval, regardless of its condition at the time of maintenance.
Probability (Likelihood)	Is the likelihood that of a specific occurrence to take place.
Process- Continuous	is a manufacturing process that is similar to the repetitive process and runs all year long. The main difference between repetitive and continuous is the production in a

	continuous process are either gases, liquids, slurries, or powders.
Process-Batch	is a manufacturing process that is similar to job shop and discrete processes. One batch or multiple batches can be produced depending on customer demands, once the demand is met the equipment is cleaned and made ready to produce the next batch.
Reliability Centered Maintenance	is a systematic and structured process to develop efficient and effective maintenance strategies for an asset or system to ensure safety, system functionality, mission compliance, and to minimize the probability of failure
Repetitive Process	is a manufacturing process where a production line produces the same product of items all year long, with minimum setup requirements or changeover. The production speed can be increased or decreased to meet customer demands.
Risk	Is the probability that a person, property, or equipment may be harmed or damaged if they are exposed to hazard. In qualitative terms, the risk is the probability multiplied by consequence.
Risk Assessment	Is a method used to identify hazards and risks in a system or component and properly analyze and assess the associated risks of the hazard, along with determining ways to eliminate the hazard.
Risk-Based Maintenance	are maintenance activities that are carried out based on the most risk-sensitive assets or systems. In this maintenance strategy, the most efficient and economic way is determined that optimize the resources distribution to achieve minimum risks and repairs.
Risk Matrix	Is a matrix that defines the risk by considering both the Probability of an event along with the consequence/ outcome of the event. The matrix is used mainly during the risk assessment process and is a helpful tool for decision making.
Risk Priority Number	is a risk measure applied that helps in the identification of critical failure modes in the design of a process. RPN has a range from 1 to 1000 and contain three main elements Severity, Occurrence, and Detection. Each element ranges from 1 to 10.

Appendix 3: Literature Review Papers Evaluation

Table 33: Literature Review Papers Evaluation:

Title	**Theory**	**Key Concepts**	**Relation to Thesis Topic**	**Possible Applications**
A combined multi-criteria approach to support FMECA analyses (A real-world case)	Proposes a new method to optimize maintenance activities of complex systems by combining both reliability analyses and MCDM methods	- Failure mode, effects, and criticality analysis (FMECA) -Risk Priority Number (RPN) -Multi-criteria decision making (MCDM): -AHP Fuzzy TOPSIS (FTOPSIS)	**High**	Thoroughly Review Concepts implemented in the topic and possible utilization with other Concepts in the literature review, considering Concepts strengths and weaknesses, as the topic focus is close to thesis focus.
A new approach for reliability-centered maintenance programs in electric power distribution systems based on a multiobjective genetic algorithm	Proposes a model to solve mathematical problems of optimizing RCM planning. The aim is to maximize the index of the reliability of the whole system along with minimizing the preventive maintenance costs.	-Mathematical models: -multiobjective, -combinatorial, -binary, -dynamic, -nonlinear -restricted	**Low**	Include in Literature Review Chapter and mentioning different ideas presented.
A novel multiple-criteria decision-making-based FMEA model for risk assessment	Proposes a new model that uses MCDM in combination with grey theory for FMEA.	-Failure mode and effect analysis (FMEA) -Risk Priority Number (RPN) -Grey relational analysis (GRA) -Multi-criteria decision making (MCDM): -Best-Worst Method (BWM)	**Medium-High**	Review Concepts implemented in the topic and possible utilization with other Concepts in the literature review, considering Concepts strengths and

				weaknesses, as the topic focus is close to thesis focus.
An integrated approach for failure mode and effects analysis based on fuzzy best-worst, relative entropy, and VIKOR methods	The goal of the paper is to enhance the performance of the classical FMEA method and to suggest a new integrated fuzzy MCDM approach for FMEA.	-Failure mode and effect analysis (FMEA) -Risk Priority Number (RPN) -Fuzzy Multi-criteria decision making (FMCDM): -Fuzzy Best-Worst Method (BWM) -Fuzzy Relative Entropy (RE) -Proximity Entropy Weight (PEW) -Similarity Entropy Weight (SEW) -Fuzzy VIKOR	**Low**	Include in Literature Review Chapter and mentioning different ideas presented.
Asset Priority Setting for Maintenance Management in the Food Industry	The thesis proposes creating and applying of a practical method of equipment classification criticality based on its importance for the production process. Three categories are used (A, B and C).	-Reliability Centered Maintenance (RCM) -Preventive Maintenance Plans (PMP) -Computerized Maintenance Management System (CMMS) -Plan Do Check Act (PDCA)	**High**	Thoroughly Review Concepts implemented in the topic and possible utilization with other Concepts in the literature review, considering Concepts strengths and weaknesses, as the topic focus is close to thesis focus.
Criticality-based maintenance of a coal-fired power plant	The thesis proposes a technique to identify the most critical components of a system, to help in the	-Preventive Maintenance (PM) -Predictive Maintenance (PRM)	**High**	Thoroughly Review Concepts implemented in the topic and possible utilization with other

	prioritization of maintenance activities. The method uses reliability and risk analysis techniques, such as (HAZOP), (FTA) and (FMECA). It also uses a MCDM, and (ANP), for ranking the critical components.	-Risk-Based Maintenance (RBM) -Reliability Centered Maintenance (RCM) -Hazard and Operability Study (HAZOP) -Fault Tree Analysis (FTA) -Failure mode and effects criticality analysis (FMECA) -Analytic Network Process (ANP)		Concepts in the literature review, considering Concepts strengths and weaknesses, as the topic focus is close to thesis focus.
Failure modes and criticality analysis of the preliminary design phase of the Mars Desert Research Station considering human factors	The paper proposes an extension to the traditional FMECA method to include the effects of human factors concerning accessibility and repairability, probability of contact, and degree of contact.	-Failure mode and effects criticality analysis (FMECA) -Hazard and Operability Study (HAZOP) -Human Design Approach (HDA) -Probabilistic Safety Assessment (PSA)	**Low**	Include in Literature Review Chapter and mentioning different ideas presented.
Identification of Critical Components using ANP for Implementation of Reliability Centered Maintenance	The paper aims to identify important factors associated with components criticality. Five major criteria are considered: complexity, safety impact, costs, functional dependency, and maintainability.	-Failure mode and effects analysis (FMEA) -Reliability Centered Maintenance (RCM) -Analytic Network Process (ANP) -Strength, Weakness, Opportunity, Threats (SWOT) Analysis	**Medium**	Review General Ideas for the framework, along with Including in Literature Review Chapter and mentioning different ideas and concepts presented.

	The 5 factors are proposed to conduct criticality analysis.			
Improving failure analysis efficiency by combining FTA and FMEA in a recursive manner	(FMEA) and (FTA) are two of the most common failure analysis methods. The paper proposes to use both methods in a recursive manner	-Failure mode and effects analysis (FMEA) -Fault Tree Analysis (FTA)	**Medium**	Review General Ideas for the framework, along with Including in Literature Review Chapter and mentioning different ideas and concepts presented.
Planning of Operation & Maintenance Using Risk and Reliability-Based Methods	The paper aims to present an application of reliability and risk-based method for planning of (OM). A life-cycle approach is used where the total expected costs in the remaining lifetime are minimized.	1) Life Cycle Model: -Damage and reliability model. -Inspection modeling. -Reliability model updating 2) Maintenance and optimization: -Condition-based maintenance -Risk-based maintenance	**Low**	Include in Literature Review Chapter and mentioning different ideas presented.
Reliability-Based Maintenance Strategy Selection in Process Plants- A Case Study	The paper presents an approach to implement (RCM) in process plants.	-Reliability Centered Maintenance (RCM) -Run-to-fail Maintenance -Preventive Maintenance -Planned Maintenance -Proactive Maintenance -Condition Based maintenance	**Medium-High**	Review Concepts implemented in the topic and possible utilization with other Concepts in the literature review, considering Concepts strengths and weaknesses, as the topic

				focus is close to thesis focus.
Reliability Evaluation and Risk-Based Maintenance in a Process Plant	The paper talks about the significances of assessing the risks and reliability of failure in the planning of maintenance schedules. A model for improving plant availability has been proposed to obtain an optimum maintenance schedule for the process plant.	-Risk-Based Maintenance (RBM) -Fault Tree Analysis (FTA) -Risk Priority Number (RPN)	**Medium-High**	Review Concepts implemented in the topic and possible utilization with other Concepts in the literature review, considering Concepts strengths and weaknesses, as the topic focus is close to thesis focus.
Risk evaluation by FMEA of supercritical water gasification system using multi-granular linguistic distribution assessment	A combined risk evaluation method utilizing FMEA is used with multi granular linguistic distribution assessments. A Best/worst and maximizing derivation methods are used to determine objective and subjective combined weights for distinguishing the importance of risk factors.	-Failure mode and effect analysis (FMEA) -Fuzzy FMEA -Risk Priority Number (RPN) -Analytic Hierarchy Process (AHP) -Multi-criteria decision making (MCDM): -Best-Worst Method (BWM) -Maximum Derivation Method (MDM)	**Medium**	Review General Ideas for the framework, along with Including in Literature Review Chapter and mentioning different ideas and concepts presented.
Risk evaluation using a novel hybrid method	The paper proposes a novel fuzzy	-Failure mode and effect	**Low**	Include in Literature Review

based on FMEA, extended MULTIMOORA, and AHP methods under fuzzy environment	hybrid model for FMEA evaluation.	analysis (FMEA) -Fuzzy Weighted Risk Priority Number (FWRPN) -Fuzzy Analytic Hierarchy Process (FAHP) -Fuzzy MULTIMOORA		Chapter and mentioning different ideas presented.
Selecting optimum maintenance strategy by fuzzy interactive linear assignment method	The paper describes a new method for selecting an optimum maintenance strategy using quantitative and qualitative data after discussion with maintenance subject matter experts. This approach has been based on (LAM) with some modifications to develop (IFLAM).	-Corrective Maintenance -(Time Based) Preventive Maintenance -Condition Based maintenance -Predictive Maintenance -Multi-criteria decision making (MCDM): -Linear Assignment Method (LAM) -Interactive Fuzzy Linear Assignment Method (IFLAM)	**Low**	Include in Literature Review Chapter and mentioning different ideas presented.

Appendix 4: Survey Questions

Below are sample survey questions which were asked to help find the results for this thesis paper:

1) Do you have experience in criticality and consequence assessment?

2) A section for each equipment (**1- 12**) and a scenario for each equipment:

    a) From the scenario explained (above), please select the appropriate Severity (S), Occurrence (S), and Detection (D):

	Severity (1-10)	Occurrence (1-10)	Detection (10-1)
Equipment (1-12)			

    a) Please select the relative importance of the equipment, from a scale of 1 to 9 for Analytic Hierarchy Analysis and Business Impact (1 to 5):

	Toxic Impacts	Environmental Impact	Fire and Explosion Impact	Personnel Impact	Business Impact
Equipment (1-12)					

2) Please fill below table to assign criteria ranking for inputs Equipment Factors:

	Criteria Ranking – Equipment Factors			
	Toxic Impacts	Environmental Impact	Fire and Explosion Impact	Personnel Impact
Toxic Impacts				
Environmental Impact				
Fire and Explosion Impact				
Personnel Impact				
Business Impact				

3) Please fille below table to assign criteria ranking for Inputs Process Factors:

	Criteria Ranking – Process Factors		
	Cost	Reliability	Risk
Cost			
Reliability			
Risk			

4) Please fill the table below from your experience regarding the reliability of each equipment:

Equipment	Availability (%)	Efficiency (%)	Quality (%)
Boiler			
Column			
Filter			
Flare			
Furnace			
Heat Exchanger			
Loading Arm			
Piping 1			
Piping 2			
Pressure Relive Device			
Pressure Vessel			
Storage Tank			

5) Please fill the below table from your experience to assign management factors:

Availability		**Cost**	
Efficiency		**Risk**	
Quality		**OEE**	