Sheffield Hallam University

An integrated framework for maintenance optimisation with petroleum industry.

MOHAMED, Abdelhafiez M.A.

Available from the Sheffield Hallam University Research Archive (SHURA) at:

http://shura.shu.ac.uk/20073/

A Sheffield Hallam University thesis

This thesis is protected by copyright which belongs to the author.

The content must not be changed in any way or sold commercially in any format or medium without the formal permission of the author.

When referring to this work, full bibliographic details including the author, title, awarding institution and date of the thesis must be given.

Please visit http://shura.shu.ac.uk/20073/ and http://shura.shu.ac.uk/information.html for further details about copyright and re-use permissions.

Sheffield S1 1WD

102 156 563 6

REFERENCE

ProQuest Number: 10697380

All rights reserved

INFORMATION TO ALL USERS
The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript
and there are missing pages, these will be noted. Also, if material had to be removed,
a note will indicate the deletion.

ProQuest 10697380

Published by ProQuest LLC (2017). Copyright of the Dissertation is held by the Author.

All rights reserved.
This work is protected against unauthorized copying under Title 17, United States Code
Microform Edition © ProQuest LLC.

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 – 1346

Sheffield Hallam University

An Integrated Framework for Maintenance Optimisation within Petroleum Industry

Abdelhafiez M A Mohamed

A thesis submitted in partial fulfilment of the requirements of Sheffield Hallam University for the degree of Doctor of philosophy

2016

Acknowledgment

During the course of this research, I was fortunate to receive all possible support and help from Professor Sameh M Saad, for which I would like to take the opportunity to emphasise my appreciation and gratitude.

I would like to thank all the participants who provided all the required data to complete this work and those who took the time to complete the questionnaires.

I am especially grateful to my parents, family and friends for consistently providing the support and the encouragement.

Finally yet importantly, I would like to dedicate this piece of work to those who have come cross my path in life and have made me think differently.

Nomenclature

AD	Asset density in the vicinity of the event of explosion ($\$/m^2$)
AHP	Analytic hierarchy process
AMI	Absolutely more important
AR	Area under the damage radius (m^2)
ARCM	Accelerated reliability centred maintenance
A_{VD}	Average demand during lead time (Time)
A_{VLT}	Average lead time in days (days)
A_{WSC}	Alternative's weight of sub criteria
B_{LC}	Booked labour costs
BP	British Petroleum
B_p	Financial loss of the facilities in terms of explosion or fire ($)
B_{pc}	Bottleneck penalty cost ($)
C	Consequence of the failure
CBM	Condition-based maintenance
CI	Consistency index
C_h	Cost of delay charges per unit ($)
CM	Corrective maintenance
C_{mc}	Corrective maintenance cost
C_{MT}	Time required completing corrective actions(hrs)
C_{pd}	Value of damaged production ($)
CR	Consistency ratio
C_{Sd}	Cost of damaged parts due to failure of another part ($)
Csp	Cost of spare parts ($)
C_{oh}	Cost of out-house maintenance ($)
C_{Wd}	Cost of cleaning non-hazardous and hazardous materials ($)
C_{wp}	Waste disposable cleaning cost ($)
D	Demand
d	Design age of part/machine
Dc	Damages cost ($)
Dch	Delay charges ($)
D_d	Daily demand
DEA	Domino effect analysis
D_{FT}	Due fine time ($)
DOM	Design of maintenance
DPD	Drilling and production equipment
EI	Equally important
EOQ	Economic order quantity
ETA	Event Three Analysis
EVM	Eigenvector method
F	Failure frequency scales
f	Frequency factor
FAHP	Fuzzy analytic hierarchy process
FGI	Finished goods inventory
FMECA	Failure mode effective and critical analysis
FTA	Fault tree analysis
$F_{\Delta t}$	Probability of failure
G	Growth factor
HAZOP	Hazard analysis and operability

Hc	Holding cost ($)
HIRA	Hazard and identification and ranking analysis
IM	Importance factor
I_{SE}	Impact on safety and environmental factor
l	Lower bound value
Lc	Legal fines in case of environmental damages ($)
LOR	Likelihood of risk
L_T	Lead time (h)
m	Middle bound value
MAX	Maximum
MC	Maintenance cost ($)
M_C	Maintenance cost factor
MCDM	Multi criteria decision making
MDT	Mean down time between failures
MIN	Minimum
MM	Maintenance management
MNV	Mean of the normalised values
MTBF	Mean time between failure
MTBM	Mean time between maintenance
MTTR	Mean time to repair
MRO	Maintenance, repairs and operations inventory
MSI	Maintenance significant items
MUT	Mean up time between failures.
N	Number of orders placed
NGM	Normalised geometric mean
OA	Operational availability
Oc	Order cost
OEM	Original equipment manufacturer
O_F	Operational flexibility factor
O_I	Operational impact factor
ORA	Optimal risk analysis
P	Physical age of the equipment
PDI	Population density in the vicinity of the event
PD1	Number of people within the ratio of impacted area
$PDF1$	Population distribution factor
PIRP	Point inspection and regular repair
P_{LC}	Production losses cost ($)
PM	Preventive maintenance
P_{mc}	Preventive maintenance cost ($)
PRA	Probabilistic risk assessment
P_{rp}	Probability of replacement
QFD	Quality function deployment
QTY	Quantity of the spare parts
RA	Risk Assessment
RBM	Risk based maintenance
RBIM	Risk-based inspection and maintenance
RCM	Reliability centred maintenance
RGBI	Reliability growth based inspection
RMI	Raw material inventory
ROP	Reordering point

RPN	Risk priority number
RRCM	Reliability and risk Centred maintenance
SIL	Safety integrity level
SL	Service level
S_{mh}	Maintenance personnel hourly rate (h/$)
SMI	Strongly more important
S_{oh}	Operator's hourly rate (h/$)
SS	Safety stock
T	Expected time between orders
TAM	Turnaround maintenance
TBM	Time-Based Maintenance
TFN	Triangular fuzzy number
t_{ip}	Time spent by maintenance personnel in carrying out preventive action (hrs)
TM	Team Managers
TMC	Total maintenance cost (h/$)
t_{su}	Machine set up time (hrs)
t_{tc}	Time spent by the maintenance personnel to repair failure (hrs)
t_{ti}	Production time loss excluding setup machine time (hrs)
u	Upper bound value
UDA	Unacceptable damaging level(m^2)
UFL	Level of an unacceptable financial loss
UFR	Unacceptable fatality rate (person)
V	Number of damaged production by barrel
VED	Vital, Essential and Desirable
VSMI	Very strongly more important
W_a	Weight of performance loss
W_b	Weight of financial loss
W_c	Weight of human health loss
W_D	Weight of environment loss
WIP	Work-in-process inventory
W_{MC}	Weight of main criteria
W_{SC}	Weight of sub criteria
X_1	Number of maintenance personnel
X_2	Number of operational personnel
Z	Number of standard deviations
α	Department's income due to one barrel ($)
α_d	Standard deviations
α_{LT}	Standard deviations for lead time in days
π	Production cycle time

Research Papers Based on this Research

Saad M Sameh and Mohamed Abdel.(2015). An optimisation model for the scheduling of preventive maintenance activities and its applications in petroleum industry. *Flexible Automation and Intelligent Manufacturing, FAIM2015.*

Saad M Sameh, Khan Nufal and Mohamed Abdel.(2015). A fuzzy-AHP multi-criteria decision-making model for procurement process. *International Journal of Logistics Systems and Management, Vol. 23, No. 1, 2016.*

Saad M Sameh and Mohamed Abdel.(2016). Optimisation of the maintenance activities and its impact on operation availability within the petroleum industry. *International Journal of Advanced Manufacturing Technology (IJAMT)(In press).*

Mohamed Abdel and Saad M Sameh (2016) Fuzzy Analytic Hierarchy Process for the Selection of Maintenance Policies within Petroleum Industry. *31st National Conference on Manufacturing Research(In press)*

Mohamed Abdel and Saad M Sameh (2016). Development of risk assessment model for equipment within the petroleum industry. *3rd IFAC Workshop on Advanced Maintenance Engineering, Service and Technology(In press)*

Abstract

Maintenance concerns abound as companies strive to increase production while guaranteeing safety, flow assurance and equipment reliability. Therefore, optimisation of the maintenance process is essential to increasing the productivity of the equipment as well as decreasing the maintenance expenditure. Thus, this research is aimed at proposing an integrated framework to optimise the major maintenance activities at strategic and operational levels including spare parts control and risk assessment within the petroleum industry.

In this research, the selection of the maintenance optimum policy for equipment within petroleum industry is dealt with at strategic level through multi criteria decision making techniques (classic and fuzzy analytic hierarchy process FAHP). At the operational level, a cost optimisation mathematical model is proposed to balance the costs of failure of a unit during operation against the cost of preventive maintenance to ensure preventive maintenance activities are kept at minimum possible cost without compromising the utilisation of equipment's performance.

Furthermore, an integrated approach between spare parts management and preventive maintenance activities is developed to create a cost effective method and ensuring the availability of parts in the stock while carrying out preventive maintenance. A risk assessment model for equipment within the petroleum industry is developed to handle the likelihood of risk and its consequences. A mathematical equation is developed to predict the likelihood of risks and identify the optimum inspection interval. In addition, set of modified mathematical equations to evaluate consequences of risk and weighing the severity of risks in specific areas is developed.

The findings of this research indicate that the proposed FAHP will clearly guide the practitioners in selecting the optimum maintenance policies at strategic level by the consideration of the related criteria and the possible alternatives for petroleum equipment. The results from the proposed mathematical model for scheduling preventive maintenance activities showed promising results in terms of cost effectiveness, reliability and availability of equipment without compromising the Inherent safety of the equipment. The integration between preventive maintenance intervals and the control of spare parts provided the petroleum companies with predictable movement of parts at the right time and hence minimises the cost of inventory. The developed equation for the consequences of risk can be used to evaluate the level of risk under different combination of sets of weight which suit the situation under consideration.

Contents

List of Figures

List of Tables

Chapter One

Introduction

This chapter is divided into six sections. The first section presents an introduction to the thesis and the second section deals with the historical background of the petroleum industry and maintenance. The third section briefly describes the problem definition and the forth section lists the thesis's aims and objectives. The last two sections respectively present the structure of the thesis and the conclusion.

1.1 Background

The contemporary business environment has raised the strategic importance of the maintenance function within organizations which have significant investment in physical assets (Tsang 2002). The performance and competitiveness of manufacturing and production companies is dependent on the reliability, availability and productivity of their production facilities (Coetzee, 1997, Madu, 2000, Fleischer et al. 2006, Muchiri et al 2011). Therefore, maintenance function needs to meet the overall target of the organization and transform business priorities into the maintenance priorities. Within many large-scale plant-based industries, maintenance costs can account as much as 40% of the operational budget and therefore improving maintenance effectiveness is a potential source for making financial savings (Eti et al 2006).

The oil and gas industry is a competitive market which requires a high performance in plants that can be translated into high availability, reliability and maintainability for equipment. Today, the expectations of high reliability and availability of equipment are so high that drives the necessity of optimising maintenance activity (Calixto 2012).The cost of maintenance in oil and gas production is the third largest cost within the production which necessitates the optimisation of this function (El-Jawhari and Collins 2014). Nevertheless, the catastrophic consequences of any failure within such industry compel the maintenance to avoid the occurrence of the failure.

The difficulty to balance between both reliability and availability of equipment on one hand and minimising the cost of maintenance on the other hand while creating a safe environment is a great deal to the petroleum industry. Aissani et al (2009) indicated that in some petroleum sectors such as "*petroleum refineries average downtime can reach 10% of the production time, and refineries are often used only at 60% of their capacity. Thus, important financial gains and safety improvements can be affected by optimising maintenance tasks*".

Various books and literature present different types of maintenance system and it has been observed that some technical and terminologies such as strategy and policy are used in different context and places to mean the same thing, so the author feels the need to define them both as they are used frequently in this thesis:

- Policy: Means the type of maintenance (corrective or preventive).
- Strategy: Means the philosophy to select the policy such as reliability-centred maintenance.

1.2 Historical Background of Petroleum Industry and Maintenance

1.2.1 Petroleum Industry

Oil has been used for purpose of lighting for thousands of years in areas where oil is found in shallow reservoirs. However, it was not until 1859 that "Colonel" Edwin Darke drilled the first successful oil well, for the sole purpose of finding oil (Devold 2013). These wells were shallow wells by modern standards, often less than 50 meters, but could give quite a large production. Soon oil had replaced most other fuels for mobile use. Despite the early attempts at gas transportation, it was not successful until after World War 2 with the development of welding techniques.

Today oil and gas are produced in different parts in the world. However, massive challenges are faced by the petroleum industry with growing environmental issues and restrictive laws as well as the challenges of sustainable energy and their remarkable challenging prices.

1.2.2 Maintenance

In the early days of the petroleum industry, maintenance was performed as "necessary evil" but over the time, the role of maintenance becomes more recognizable. The need for providing better services with the petroleum industry as any other industries requires the development of maintenance programme. The first recognized policy was corrective maintenance or run to failure policy.

The second generation of maintenance was the preventive maintenance in the form of the periodic and the last generation is predictive maintenance or condition maintenance. Different philosophies have been developed to run these policies such as reliability centred maintenance (RCM) and risk based maintenance, which will be extensively discussed in the thesis.

1.3 Problem Definition and Research Questions

The petroleum industry is a sensitive industry when it comes to maintenance and its recognized role in terms of added value to the production line. The reason for this sensitivity is the high demand of controlling the high reliability and availability of equipment and the catastrophic consequences of failures in such industry.

The general conception of the function of maintenance is to prevent the failure of occurrence, which is correct to some extent. However, to clearly identify the role of maintenance, considerations to the reasons of failure, which might include the faulty designation, abuse of equipment by the operator and as a sequence of imperfect maintenance planning should be analysed. Therefore, the role of maintenance is to create a programme that utilizes the equipment productivity, to minimise the interruption to the production line and within the least spending.

In the petroleum industry, maintenance plays a significant role to bring the assets reliability and availability into a desirable predefined level while decreasing the expenses. In order to explicitly understand the problem the author summarizes it in the following questions:

1. What are the major activities that should be included within the integrated maintenance framework?
2. What is the most appropriate maintenance philosophy that can comprehensively lead to the selection of the most appropriate maintenance policy?
3. What is the most suitable methodology to recognize the optimum maintenance intervals?
4. As the spare parts have a big portion of the maintenance's cost, what is the most appropriate approach to optimise the spare parts inventory used for maintenance?
5. Finally, risk assessment is one of the major activities with the petroleum industry and, therefore, how can it be improved to reflect the likelihood and consequences of the failures?

Solving these problems demands a successful cooperation between maintenance department and other involved departments such as inventory department. To optimise the maintenance within the petroleum industry, generic integrated framework is proposed and the next section discusses the main aim and objectives of building the framework.

1.4 Aims and Objectives

1.4.1 Aim

The principle aim of this research is to develop an integrated framework that optimises major maintenance activities at strategic level, operational level, inventory control and risk assessment within the petroleum companies in order to maximize availability, reliability, and safety of assets while minimizing the cost of maintenance.

1.4.2 Objectives

In order to achieve the aim stated above, the following objectives will be undertaken to optimise the major maintenance activities within petroleum industry:-

- Development of a strategic maintenance policy for petroleum industry which covers the whole area of the field by using classic and fuzzy analytical hierarchy process to identify criteria, sub-criteria and alternatives that can lead to the optimisation of maintenance policy's selection.
- Development of a mathematical model for the operational level to identify the optimum interval at which the preventive maintenance activities should be carried out (schedule of preventive maintenance policy).

- Development of an integrated approach between maintenance and inventory management to control the availability and the level of spare parts required at the time of maintenance activities.
- Development of a risk assessment model that guides the maintenance on assessing the risk for the petroleum equipment.

1.5 Structure of the Thesis

This section outlines the structure of the thesis including a summary of each chapter. It provides guidance to the reader to understand the direction of the study and know the sequence and placement of various concepts.

1.5.1 Chapter One: Introduction

The author provides the reader with an introduction to the research focus, the aims and objectives and the context of the study. In addition, the chapter provides the reader with the problem definition and the research questions that interested the author to carry out this research.

1.5.2 Chapter Two: Literature Review

Chapter two comprehensively covers related literature review regarding maintenance generally and within the petroleum industry. It includes the various strategies for the selection of the maintenance policies and different methods for the scheduling of preventive maintenance activities. Moreover, the chapter provides literature review related to the inventory management and existing frameworks for controlling the policy of spare parts as well as insights to models and frameworks for controlling maintenance within the petroleum industry. The assessment of risk is covered including the importance and the role of the assessment of risk within the petroleum industry. Finally, the conclusion is drawn and the research gaps are emphasised.

1.5.3 Chapter Three: Research Methodologies and the Proposed Integrated Framework

The third chapter demonstrates concisely each methodology used to optimise a certain activity within the proposed integrated maintenance framework. As the major maintenance activities are targeted to be optimised, each activity's method will be outlined and later in corresponding chapters, these methods will be extensively illustrated. The proposed integrated maintenance framework is then presented with an outline of the relevant terminologies that are used such as, optimisation and the required data.

1.5.4 Chapter Four: Maintenance Strategic Level

In this chapter, the problem of the selection of the most appropriate maintenance policy is presented. The proposed model for the selection of the maintenance policy within the petroleum industry is defined and the application of different classic analytic hierarchy "Pairwise Matrix Evaluation" methods is demonstrated. Fuzzy analytic hierarchy process is applied and compared at the end of the chapter to the results calculated from classic AHP including sensitivity analysis.

1.5.5 Chapter Five: Maintenance Operational Level

Chapter five demonstrates the proposed mathematical model for the optimisation of preventive maintenance scheduling intervals. The mathematical model is explained and the developed equations are extensively illustrated. The implications of the proposed mathematical model are demonstrated and at the end of the chapter, the author draws the conclusion of the applied method.

1.5.6 Chapter Six: An Integrated Approach between Preventive Maintenance and Spare Part Control

Chapter six illustrates the integrated approach between maintenance intervals and spare parts control. It discusses the relationship between the maintenance intervals and the movement of spare parts. A case study is presented to show the impact of the integrated approach on the inventory level with different assumptions of lead-time.

1.5.7 Chapter Seven: Risk Assessment Model for Petroleum Equipment

Chapter seven presents the proposed risk assessment model for equipment within the petroleum industry. A development of risk equation is presented to assess the likelihood of the risk besides qualitative risk assessment. The consequences of the risk are also evaluated as a loss on four main areas including system performance loss, financial loss, human health loss and environment loss.

1.5.8 Chapter Eight: Conclusions, Contribution to knowledge and Future Work

Chapter eighth summarizes the conclusion of the thesis and the outline of the proposed methodologies and contribution to knowledge within the thesis are discussed. The recommendations for future work that are related and extended from this work are advised.

1.6 Conclusion

In this Chapter, an introduction to the petroleum industry and maintenance's importance were provided. The historical development of the petroleum industry and maintenance philosophy were discussed to understand the nature of such competitive industry. The definition of the problem, the aims and objectives were discussed to highlight the main target of the thesis. The structure of the thesis in terms of chapters was outlined to simplify it for the readers. The next chapter will deliver literature review and latest developments in maintenance and the related topics associated with the framework.

Chapter Two
Literature Review

This chapter provides a comprehensive background to the maintenance within the petroleum industry. The definition of maintenance, its policies and its role within the petroleum industry are extensively demonstrated. The literature review also covers topics that are related to the selection of maintenance policy, determining the optimum maintenance interval, spare parts control and risk assessment within the oil and gas field.

2.1 Introduction

Contemporary business environment has raised the strategic importance of the maintenance function in organizations that have significant investment in physical assets. The high cost proportion of maintenance in operation costs within manufacturing and production industries has drawn attention to the importance of planning and controlling of maintenance actions to minimize the operational costs.

The aim of this chapter is to present a comprehensive and yet concise literature review of the major areas that related to maintenance in general and within the petroleum sector in particular. The notion for this chapter is to provide the readers of this thesis with a background of the relevant topics to provide a better understanding of the contribution suggested by the author.

The chapter starts with a background of maintenance management within the oil and gas industry, including the history of maintenance, the current existing strategies to select maintenance's policy and the methods used to select the time of conducting maintenance overhauls where the majority of the maintenance actions are carried out. This chapter extends to explain inventory management and relevant topics such as inventory control, economic reorder point and safety stocks. Another aspect covered within the literature review is risk assessment within the petroleum industry and different methodologies used to estimate the likelihood and the consequences of the risks.

2.2 Definition of Maintenance

The term maintenance can be defined as all actions appropriate for retaining an item/part/equipment in, or restoring it to a satisfactory condition (Dhillon

2002). Márquez (2007) defined maintenance management (MM) as all activities of the management that determine maintenance objective or priorities assigned and accepted by the management and maintenance teams, "strategies" defined as the management methodology to achieve maintenance objectives, and responsibilities and the implementations means such as maintenance planning and maintenance control. Adebimpe et al (2015) extended on the definition of maintenance and its actions that includes the repair of broken equipment, the preservation of equipment conditions and the prevention of their failure. This ultimately reduces production losses and downtime and also reduces environmental and associated safety hazards. Due to the increasing pressure of high competition and stringent environmental and safety regulations, maintenance has shifted from being perceived as a “necessary evil” to being recognized as an effective tool for increased profitability. Maintenance has become an integrated part of the production process rather than a supporting or peripheral activity. Developing effective and optimum maintenance strategies and models has thus become a subject of research in both academic and industry areas.

2.3 Maintenance Policies

Tremendous change have occurred in engineering since the industrial revolution, but perhaps the most dramatic changes have occurred in the last sixty years (Parida and Kumar 2006). As a result of these changes as well as the growth of the complexity of assets, maintenance management has developed to maintain the plant's more complicated machinery with respect to the type of industry and the overall target of that industry. Another

Important reason of the development of maintenance is the demand on productivity, availability, quality, safety and environment (Arunraj and Maiti 2007). Maintenance can be categorised into different classifications according to its actions. Maintenance can mainly be classified into two types: Corrective Maintenance (CM) and Preventive Maintenance (PM) (Waeyenbergh and Pintelon 2004; Li et al., 2006). Planned maintenance could be time-based or condition-based (Duffuaa et al., 1998). Each plant's assets or equipment can be associated with one or more maintenance policy throughout its lifecycle (Hossam et al 2003).

The management system of Point Inspection and Regular Repair (PIRR) is regarded as the present core of maintenance and management for onshore and offshore oil field equipment, which mainly adopt corrective maintenance (CM), Time-Based Maintenance (TBM) and Condition-Based Maintenance (CBM) (Perrons et al 2013 and Doostparast et al 2014).

2.3.1 Corrective Maintenance (CM)

In the case of CM policy, an item is allowed to fail before maintenance is implemented. CM is still being used until today due to the fact that CM can be useful and add value to the plant under certain criteria such as the criticality of the machine and the effect of the failure (Waeyenbergh and Pintelon, 2002). Balasaheb and Milind (2012) mentioned that CM is the first and the basic policy that appeared in the industry. CM is also referred to as, failure based maintenance, breakdown maintenance or run to failure strategy.

2.3.2 Preventive Maintenance (PM)

PM refers to the action of maintenance implemented to prevent the occurrence of failure (ETI et al 2006). Basically, the notion of this policy is to predict the wear and tear or life of equipment by using different approaches to prevent failure from taking a place. In general, the amount of equipment failure can be reduced if the preventive maintenance strategies are correctly selected (Balasaheb and Milind 2012). Most common forms of PM are time-based maintenance (TBM) and condition-based maintenance (CBM).

2.3.2.1 Time-Based Maintenance (TBM)

In this policy, maintenance is scheduled in advance to prevent failure. It focuses on preventing failures through replacing components at particular time. It assumes that the machine component's life is predictable, and maintenance is based on hours of run or calendar time elapsed. This is suitable for repeatable degradation modes, wear process for example. In this policy replacement or repair is carried out at a fixed time after the installation of a facility, which is generally independent of its condition. The time period used to construct a maintenance schedule can be either calendar time or component running time (Ahmad et al 2011).

2.3.2.2 Condition Based Maintenance (CBM)

Maintenance decision is made depending on measured data. Vibration monitoring, lubrication analysis, thermography, visual inspection and ultrasonic testing are commonly used approaches to collect data (Mobley 2002). Based on the data analysis, whenever the monitoring level value exceeds the normal the component is either repaired or replaced. The use of CBM may lead to considerable reductions in production cost, capital investment and increments in the quality rate, profits, and market share. However, limitations in data coverage and quality reduce the effectiveness and accuracy of the condition-based maintenance strategy (Alnajjar and Alsyouf 2003).

2.4 The Role of Maintenance

"The primary objective of planned maintenance is the minimization of total cost of inspection and repair, and equipment downtime (measured in lost production capacity or reduced product quality" (Mann et al 1995).

Luxhøj et al (1997); Pradhan and Bhol (2006) stated that the importance of maintenance to industry can be measured by:

- Accounting of the total maintenance cost.
- Percentage of maintenance cost to total production cost or capital cost in assets.
- Total number of personnel working with maintenance or percentage of maintenance personnel to total number of production personnel.
- Possible consequences for lack of maintenance: financial, environmental, human, equipment damage.

Bevilacqua and Bragliab (2000) described the role of maintenance in some industries and how it is the second highest or even the highest element of operating costs. As a result, in only 30 years it has moved from almost nowhere to the top of cost control priority.

According to Utne et al (2012), scheduled and unplanned shutdowns such as repairs, overhauls, replacements and require parts to shutdown are the major contributor for the expenses to oil drilling platforms and processing plants. Apart from these long period maintenance activities, shorter types of planned and unplanned shutdowns are also cause for production loss and revenue loss. Tang et al 2015 outlined the unreasonable maintenance policies, surplus or insufficient maintenance, exorbitant maintenance costs and increasing failure frequency, which have caused a great influence to production safety and economic cost in the oil and gas exploitation process.

2.5 Maintenance Policy Selection Problem

Effective maintenance management involves a multidisciplinary approach where maintenance is viewed strategically from the overall business perspective to translate those priorities into maintenance tasks. Estimating the best set of maintenance policies for different failure modes is a hard and complex task. This selection requires the knowledge of various factors such as safety aspects, environmental problems, costs and budget constraints, manpower utilization, mean time between failure (MTBF) and mean time to repair (MTTR) for each piece of equipment (Bertolini and Bevilacqua 2006). Oil and gas companies as any other companies are in favour of optimisation of maintenance, to provide the highest availability of equipment with minimization of the running maintenance cost with respect to environment and safety (Azadeh et al 2009).

Maintenance management process can be divided into two main levels: strategic level "including the definition of the policy to be implemented" and operational level "considers the implementations of the strategy" (Márquez 2007). In addition to that Márquez (2007) stated that strategic level is normally neglected by the maintenance department which leads to the probability of selecting inappropriate maintenance policy for a machine. Hong et al (2012) acknowledged that the wrong selection of the optimal maintenance policy leads to the increase in failure rate and also affects the productivity of the production line.

Different approaches and philosophies have been implemented to manage maintenance on the strategic levels within the oil and gas companies such as Reliability centred maintenance (RCM) and risk based maintenance (RBM). Each approach has its uniqueness and priorities to deal with managing maintenance. In the following section, explanations of the most applied approaches to manage maintenance on the strategic level are described.

2.5.1 Reliability-Centered maintenance (RCM)

Reliability-centred maintenance (RCM) was first developed within the aircraft industry and later adapted by several other industries and military branches (Rausand 1998). Reliability-centred maintenance (RCM) is an engineering framework that enables the definition of a complete maintenance regime and as the name indicates, reliability is the main point (Selvik and Aven 2011). RCM is a well-established analysis method for preventive maintenance planning. As its name indicates, reliability is the main point of reference for the planning of maintenance. However, consequences of failures are also assessed. RCM is one of preventive maintenance strategies to incorporate new understanding to the ways equipment fail (Deshpande and Modak 2002). The methodology has been available in the industry for over 30 years, and has proved to offer an efficient strategy for preventive maintenance optimisation . RCM is a technique initially developed by the airline industry that focuses on prevention of failures whose consequences are likely to be serious (Selvik and Aven 2011).

2.5.1.1 Reliability Centered Maintenance Phases

The RCM analysis process focuses on the functions of plant and equipment, the consequences of failure and measures to prevent or cope with functional failure. Moubray (1997) identified the steps to implement RCM including determining key functions and performance standards, determining possible function failures, determining likely failure modes and their effects, selecting feasible and effective maintenance strategies, scheduling and implementing selected strategies, and optimising tactics and programs. Selvik and Aven (2011) summarised the phases of RCM methodology by the following three phases.

- Identification of Maintenance Significant Items (MSI).
- Assignment of suitable PM tasks for the MSI.
- Implementation and update of the PM tasks.

Moubray (2000) suggested that due to the time consuming nature of the classical failure mode effective and critical analysis (FMECA), in many places only critical equipment are analysed by RCM method. Rausand (2008) stated that RCM has significant start-up costs associated with staff training and equipment needs, as well as savings potential is not readily seen by management which can be a huge disadvantage of using RCM. Selvik and Aven (2011) stated that one of the shortcomings of RCM is traced to the limited assessments of risk and uncertainties. Jagathy and Deepak (2013) suggested that refineries and process plants find it difficult to adopt this standardized methodology of RCM mainly due to the complexity and the large amount of analysis that needs to be done, resulting in a long drawn out implementation, requiring the services of a number of skilled people.

2.5.2 Risk Based Maintenance (RBM)

Krishnasamy et al (2005) defined RBM as the selection of maintenance policy depending on the assessment of the risk. Dey (2001) developed a risk based model that reduces the amount of time spent on inspection and to reduce the cost of maintaining petroleum pipelines. He used Analytic Hierarchy Process (AHP) to identify the factors that influence failure on specific segments and analyzed their effects by determining probability of risk factors and the severity of failure is determined through consequence analysis. Accordingly he suggested the inspection time and the maintenance type for the pipeline.

Tixier et al (2002) listed and identified different risk analysis methodologies, and categorized them from diverse references into deterministic, probabilistic, and combination of deterministic and probabilistic approaches. The main aim of this methodology is to reduce the overall risk that may result as the consequence of unexpected failures of operating facilities (Khan and Haddara, 2004). They divided RBM methodology into four modules: identification of the scope, risk assessment, risk evaluation, and maintenance planning. Dey et al (2004) used risk-based maintenance model to select specific inspection and maintenance method for specific section in line with its probability and severity of failure for oil and gas pipeline in the Gulf of Thailand. Their work came to generate guidelines for planning the pipeline maintenance program (Arunraj and Maiti, 2007). The inspection and maintenance activities which are planned using RBM are prioritized on the basis of quantified risk caused due to failure of the components, so that the total risk can be minimized. The high-risk components are inspected and maintained usually with greater frequency and thoroughness and are maintained in a greater manner, to achieve tolerable risk criteria. They classified three categories of the method (deterministic, probabilistic and deterministic and probabilistic) into qualitative, quantitative and semi-quantitative and identified the risk-based maintenance methodology to consist of six modules which are - hazard analysis, likelihood assessment, consequence assessment, risk estimation, risk acceptance and maintenance planning.

2.5.3 Multi Criteria Decision Making (MCDM)

Multi Criteria Decision Making (MCDM) refers to finding of the best solution or decision to a problem from all of the feasible alternatives in the presence of multiple, usually conflicting, decision criteria. Priority-based, outranking, distance-based and mixed methods could be considered as the primary classes of the current methods. The MCDM techniques generally allow to structure the problem clearly and systematically. With this characteristic, decision makers have the possibility to easily examine and scale the problem in accordance with their requirements (Işıklar and Büyüközkan 2007). Cinelli et al (2014) stated that in their comparison study between MCDM tools "*the review has shown that there is not a clear agreement among different authors concerning some comparison criteria*". Therefore, the selection of a certain MCDM tools to fit the problem under investigation is an essential step to ensure the utility of each tool. Velasquez and Hester (2013) and Cinelli et al (2014) presented an analytical comparison study of multi-criteria decision making methods including the strengths and weakness of each method as shown in table (2-1).

Table 2-1: Comparison between MCDM Tools

Method	Strengths	Weakness
Analytic Hierarch Process (AHP)	• Availability of software with good graphical capabilities • Clear hierarchy structure. • Use of qualitative • Possibility of trades of between criteria • Rank reversal can occur	• The use of rigid scale might not reflect uncertainty
Analytic Network Analysis ANP	• Applicable in the case of strong horizontal interrelationship between sub-criteria	• It requires a large amount of questionnaire to fill in. • It might be too complicated
Multi Attribute Utility Theory (MAUT)	• Availability of software • Takes uncertainty into account • Can incorporate preferences.	• Limited graphical capabilities • Needs a lot of input • Preferences need to be precise • Not flexible in terms of trade-offs between criteria • Possibility of re-evaluating results if new information becomes available is limited
Case-Based Reasoning (CBR)	• Not data intensive • Requires little maintenance • Can improve over time • Can adapt to changes in environment	• Sensitive to inconsistent data • Requires many cases
Goal Programming (GP)	• Capable of handling large-scale problems • Can produce infinite alternatives	• It's ability to weight coefficients • Typically needs to be used in combination with other MCDM methods to weight coefficients
Elimination and Choice Expressing Reality (ELECTRE)	• Takes uncertainty and vagueness into account	• Its process and outcome can be difficult to explain in layman's terms • Outranking causes the strengths and weaknesses of the alternatives to not be directly identified
Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE)	• Easy to use; • Does not require assumption that criteria are proportionate	• Does not provide a clear method by which to assign weights
Technique for Order Preferences by Similarity to Ideal Solutions (TOPSIS)	• Has a simple process • Easy to use and program • The number of steps remains the same regardless of the number of attributes	• Its use of Euclidean Distance does not consider the correlation of attributes • Difficult to weight and keep consistency of judgment

2.5.4 Analytic Hierarchy Process (AHP)

The analytic hierarchy process (AHP) is a structured technique for organizing and analysing complex decisions, based on mathematics and psychology. It was developed by Thomas L. Saaty in the 1970s and has been extensively studied and refined since then (Wind and Saaty 1980). Saaty (1982) discussed the application of AHP and mentioned that the selection of maintenance policy for a pipeline to be a team effort which require a group of people to make the decision.

Saaty (1990) stated that t AHP not only helps the analysts to arrive at the best decision, but also provides a clear rationale for the choices made as well as enables the analyst to measure consistency. (AHP) (Torfi et al 2010). Decision-making becomes more sophisticated since the selection methods have different level of preferences in mentioned criteria (Shaverdi and Barzin 2012).

Bevilacqua and Braglia (2000) mentioned the main steps of Analytic hierarchy process AHP that Saaty had identified:

2.5.4.1 Step 1: Model the Hierarchy Structure:-

This is done by including the main goal at the top, followed by the main criteria, sub criteria and alternatives. Understanding the nature of the industry is important to identify the elements of each level.

2.5.4.2 Step 2: Establish Priorities among the Elements of the Hierarchy

This is performed by making a series of judgments based on pairwise comparisons of the elements. Vidal et al (2011) explained that the weights determine the importance of alternatives' utilities in the context of specific criteria.

2.5.4.3 Step 3: Check the Consistency of the Matrix

The AHP enables the analysts to evaluate judgements with the consistency ratio (CR). The judgements can be considered acceptable if consistency ratio is less than 0.1 ("10%"), and if it is more than 10% then the matrices which have the expert's judgments are not acceptable and should be carried out again. Saaty (1977) has proposed a consistency index (CI), which is related to the eigenvalue method (Ishizaka and Labib 2009).

2.5.4.4 Step 4: Pairwise Matrix Evaluation

Once a judgement matrix has been developed, a priority vector to weight the elements of the matrix is calculated. Several methods for deriving local priorities ("the local weights of criteria and the local scores of alternatives") from judgment matrices have been developed. Wang et al (2007) listed some of the pairwise matrix evaluation method:

- Mean of the normalised values (MNV).
- The normalised geometric mean (NGM).
- The Eigenvector Method (EVM).

2.5.4.4.1 Mean of the Normalised Values (MNV)

This method is considered to be the oldest method (Ishizaka and Lusti 2006). The method consists of three main steps as followed:

1. Summation of the elements of the column j

All the elements of the column j of the matrix are summed up as shown in equation (2-1) (Ishizaka and Labib 2009). In this case, the comparison of the alternatives i and j is given by Pi/Pj

$$\frac{p_1}{p_j}+\frac{p_2}{p_j}+\frac{p_3}{p_j}\dots\dots.\frac{p_4}{p_j}+\frac{p_n}{p_j}=\frac{\sum_{i=1}^{n}Pi}{Pj} \qquad \text{2-1}$$

Where:-

i and j are any alternatives of the matrix.

pi is the priority of the alternative i.

2. Normalization of the column j

In this step, the normalized value is calculated by dividing the comparison resulted from step one by resulted column's sum (equation 2-2).

$$\frac{\frac{p_i}{p_j}}{\frac{\sum_{i=1}^{n}Pi}{Pj}}=\frac{P_i}{P_j}\times\frac{P_j}{\sum_{i=1}^{n}P_i}=\frac{P_i}{\sum_{i=1}^{n}Pi} \qquad \text{2-2}$$

3. Mean of row i: In the last step to obtain the priorities from the comparison matrix, the mean of each row is calculated applying equation (2-3).

$$\left(\frac{P_i}{\sum_{i=1}^{n}Pi}+\cdots+\frac{P_i}{\sum_{i=1}^{n}Pi}\right)\times\frac{1}{n}=\frac{n\times p_i}{\sum_{i=1}^{n}Pi}\times\frac{1}{n}=\frac{P_i}{\sum_{i=1}^{n}Pi} \qquad \text{2-3}$$

2.5.4.4.2 The Normalized Geometric Means (NGM)

In this approach, an alternative measure of the Priority which is formed by taking the root of the product matrix of row elements divided by the column's sum of row geometric means as shown in equation (2-4) (Ishizaka and Lusti 2006).

$$\sum_{i=1}^{n}1\sum_{j=1}^{n}1\left(\ln(a_{ij})-\ln(\frac{P_i}{P_j})\right) \qquad \text{2-4}$$

Where:-

a_{ij} is the comparison between iand j and Pi is the priority of i.

NGM method is applied to the collected data and to deal with the comparison matrixes to compare its out comes with other methods applied. The priorities from the main criteria matrix: "cost, availability, reliability and safety" are calculated with the use of NGM to demonstrate the methodology.

1 - Building the comparison matrix with respect to the upper level.

2- Equation (2-5) is applied to calculate the geometric mean for each row p

$$p = \sqrt[n]{a.b.c \ldots .n} \qquad 2\text{-}5$$

2.5.4.4.3 The Eigenvector Method (EVM)

The idea of a priority vector has much less validity for an arbitrary positive reciprocal matrix $A = (a_{ij})$ than for a consistent and a near consistent matrix (Saaty, 1997). A positive n by n matrix is reciprocal if $a_{ij} = 1/a_{ij}$ (Saaty 2003). It is considered to be consistent if $a_{ij}\, a_{ik} = a_{ik}, i, j, k = 1, \ldots, n$. From $a_{ij} = a_{ik}/a_{jk}$ we have $a_{ij} = \frac{a_{jk}}{a_{ik}} = a_{ij}{}^{-1}$ and a consistent matrix is reciprocal.

The custom is to look for a vector $w = (w_1, \ldots .. w_{n)}$ in which the matrix $w = (w_i/w_j)$ is close to $A = (a_{ij})$ by minimizing matrix (Saaty 2003).

2.5.4.5 Step 5: Sensitivity Analysis

The last step of the decision process is sensitivity analysis, where the input data are slightly modified in order to observe the impact of this on the results. This allows checking how the outcome changes depending on changes in criteria weights. If the ranking does not change, the results are said to be robust. Expert Choice allows different sensitivity analyses, where the main difference is the various graphical representations (Ishizaka and Labib 2009).

2.5.5 Implementation of AHP for Maintenance Policy Selection

Generally AHP has been implemented in different sectors of industry as a support tool to the decision makers to select the most suitable decision. Bevilacqua and Braglia (2000) described the use of Analytic Hierarchy Process (AHP) for selecting the best maintenance strategy for an important Italian oil refinery.

They created the hierarchy scheme (figure 2-1) and considered different alternatives of maintenance strategies to improve the effectiveness of the methodology. Sensitivity analysis was coupled with AHP technique and they arrived at the conclusion that AHP technique makes it possible to approach the decision making problem in a comprehensive way while taking several factors into account. In comparison, this capacity is more difficult to obtain when using conventional methodologies such as FMECA.

AHP is able to manage a large number of possible alternatives in an efficient way and it can integrate both qualitative and quantitative information. With AHP a direct quantitative judgement of the relevant maintenance factors is not necessarily required by the maintenance manager.

The pairwise comparisons are preferred by the manager when several intangible criteria have to be treated, as is the case with maintenance selection. In addition, AHP is the only known MCDM model that can measure the consistency of the decision maker and its procedure is readily available in decision-making software packages from several commercial software sellers.

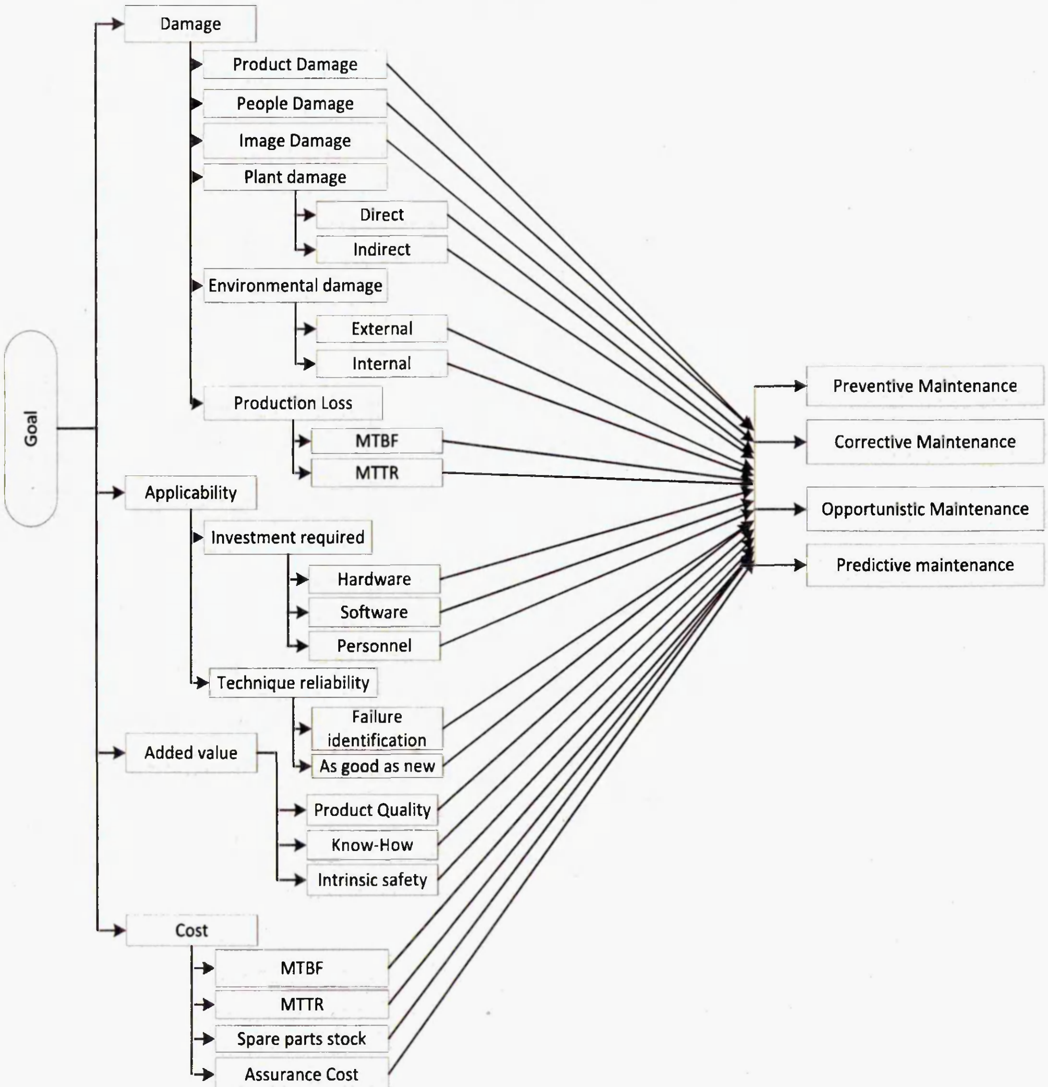


Figure 2-1: AHP for Maintenance in Oil Refinery (Bevilacqua, and Braglia 2000)

In 2004 Dey et al used pipelines data, collective experiences of the pipelines operators, existing knowledge base, analytic hierarchy process (AHP), a multiple criteria decision making technique and weight methods to develop a risk-based inspection and maintenance model for offshore pipelines in the Gulf of Thailand, aiming to reduce the consequences of failure.

Bertolini and Bevilacqua (2006) proposed a combined AHP with goal programing GP model. In particular, in the model described here the AHP analysis provides the priority vector of the possible maintenance policies (corrective, preventive and predictive) for each failure type revealed. The use of AHP allows defining a three level hierarchical structure: the top level represents the goal of the analysis (in this case the maintenance policy definition), the second level is related to the relevant criteria used (occurrence, severity and detectability), the third level defines the possible alternatives.

Dawotola et al (2009) proposed a combined Analytic Hierarchy process (AHP) and Fault Tree Analysis (FTA) to support the design, construction, inspection and maintenance policy of oil and gas pipelines by proposing an optimal selection strategy based on the probability of failure and consequences of failure. They combined AHP and FTA into a model and their methodology comprised of implementation of Analytic hierarchy process followed by a Fault Tree analysis. AHP is used in the decision making to estimate the likelihood of an event, by establishing relative importance of each contributing factors, while Fault Tree Analysis is directed at the important failure criteria identified by AHP.

Dawotola et al (2010) proposed a decision based method for risk management of oil and gas pipelines. The method is based on a Multi Criteria Decision Analysis (MCDA) framework, utilising an Analytic Hierarchy Process (AHP) to prioritise and optimise oil and gas pipeline's inspection and maintenance. After the implementation of their work on three pipelines in Nigeria, they found that the highest risk factor on pipelines was that of the activity of third party.

Achilla et al (2015) presented AHP model for the selection of the most appropriate maintenance policy for petroleum pipeline. Four types of maintenance policies were considered (corrective, time based, condition based maintenance and design of maintenance (DOM). DOM was considered as one of the alternatives which is a method to minimise the maintenance interval through the span life of the pipeline. Different factors were considered such as corrosion, external interference, operational defects and natural hazards. Their results showed that CBM was the most suitable policy for the pipeline and they believe that their mode is applicable.

2.5.6 Fuzzy Analytic Hierarchy Process (FAHP)

The key idea of fuzzy set theory is that an element has a degree of membership in a fuzzy set (Ayağ and Özdemir 2006). The FAHP methodology is designed to an alternative selection and justification problem by integrating the concept of fuzzy set theory and hierarchical structure analysis (Özdağoğlu and Özdağoğlu 2007).

Timothy (2010) also recognized that human assessment on qualitative attributes is always subjective and thus, imprecise. Therefore, a conventional AHP seems inadequate to capture decision maker's requirements explicitly. In addition to that, fuzzy systems are very useful in a situation involving high complex systems. The use of fuzzy methodology allows the decision maker to incorporate both qualitative and quantitative data into the decision model. Kabir and Hasin (2011) listed more reasons of selecting FAHP over AHP and how integrating fuzzy sets with AHP can overcome some of these classic AHP limitations:

1. The AHP method is mainly used in nearly crisp decision applications.
2. The AHP method does not take into account the uncertainty associated with the mapping of one's judgment to a number.

3. A decision maker's requirements on evaluating alternatives always contain ambiguity and multiplicity of meaning that cannot be emphasized by conventional AHP.

AHP breaks down a complex decision by considering all the relevant and available solutions to arrive at the most suitable decision. However, it does not consider cognitive factors of human judgement (Sarfaraz, et al. 2012). Sharma and Yu (2014) stated that Fuzzy AHP is the extension of Saaty's theory and many researchers have proved that fuzzy AHP shows more sufficient description in decision-making process compared to the classical AHP method.

2.5.6.1 Applications of FAHP

FAHP has been implemented in different sectors to assist decision-makers to arrive at the most appropriate decision. The earliest work in fuzzy AHP appeared in Laarhoven and Pedrycz (1983), which compared fuzzy ratios described by triangular membership functions. They applied their extended method on the selection of candidates for a vacancy and they concluded their study by agreeing that FAHP has a positive add-value to support the decision-makers. Chengzhong (1984) proposed another method, which is the altered gradient eigenvector method, to derive the priority by the idea that the information of pairwise comparison of elements can be represented by an upper triangular matrix, and proved that the result is the same as that of the Eigenvector method in the case of consistency.

Ruoning and Xiaoyan (1992) presented extend FAHP, starting from the viewpoint of actual applications of AHP, considering the method of group decision-making in complex systems and the fuzziness of judgment in a pairwise comparison of projects. They constructed the fuzzy judgment matrix by using a set-valued statistics method on a continuous judgment scale and proved that every element of the fuzzy judgment matrix can be represented by a positive bounded closed fuzzy number. They demonstrated their theory by applying it on three selected colleges to evaluate their standard of running a school. Chang (1996) demonstrated the applications and the detailed step of FAHP using a triangular fuzzy number on the same example Laarhoven and Pedrycz (1983).

Kwong and BAI 2002 applied the Fuzzy AHP to determine the importance of customer requirements in quality function deployment (QFD). They used the triangular fuzzy number (TFN) instead of conventional AHP and listed the advantages of using the fuzzy sets over classic sets as follows:

1. The preference of using fuzzy AHP over conventional AHP because of the nature of human judgement in the comparisons of customer requirements which is rather fuzzy in nature.
2. The adoption of fuzzy number can allow the design team of QFD to have freedom of estimation regarding the overall customer satisfaction.

Wang et al (2007) used the fuzzy AHP for the selection of maintenance strategies in a power plant - Hangzhou Pro-Energy Heat and Power Co. Generated framework was used to show the criteria, sub-criteria and alternatives (figure 2-2) and using the fuzzy sets the comparison matrix was established. Results showed that the predictive maintenance strategy was the most suitable for boilers.

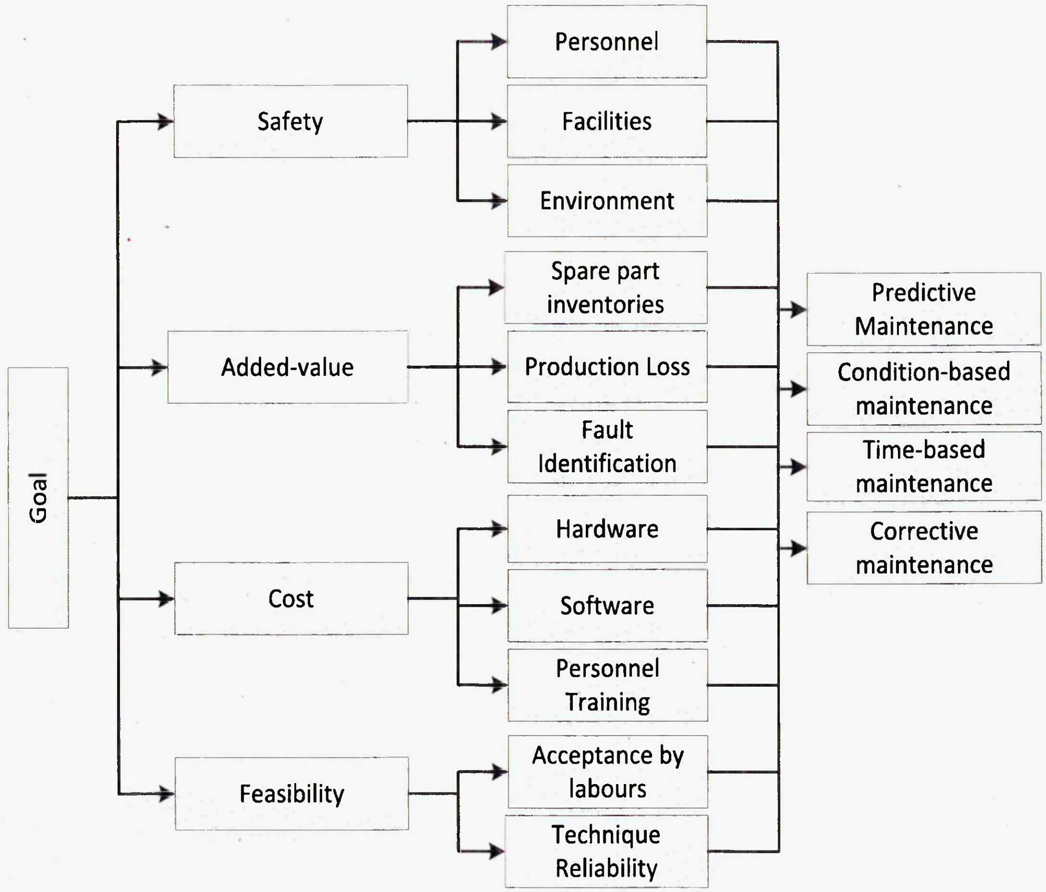


Figure 2-2: Hierarchical Structure of the Fuzzy Analytical Hierarchy Process (Wang et al 2007)

Peng et al (2007) proposed that the FAHP model for optimum integrity maintenance decision-making for oil and gas pipeline is based on the assessment of the quantity of risk and distinguished the high-risk pipes with unacceptable risk level. Four criteria were considered, they are: to include person factors, fieldwork difficult degree, field management and environment condition to impact the pipeline maintenance. The model which was aimed to establish the most suitable measurement to enhance the maintenance system concluded that for the best selection of measurement, a team-work to decide the measurement is preferred than be decided by only the maintenance manager.

Tang et al (2015) stated that due to the previous maintenance decision-making process without using the mathematical model and decision-making theory, there were some undesirable phenomena and problems during the maintenance and management for oil and gas drilling and production equipment (DPE). They presented a framework for making maintenance decisions for DPE to restraint safety accidents and economic losses in the oil and gas exploitation process. They summarized four categories influence factors, including eight influence factors to evaluate the importance level of the DPE. Eight influence factors were regarded as the evaluation indexes and their scoring criteria were defined to quantify the result of subjective evaluation. The evaluation model calculating the importance level of the DPE was established based on the AHP method. They divided the DPE into three categories: Class A, B and C, based on their importance level values.

2.6 Scheduling the Maintenance Interval

The majority of the maintenance tasks within the petroleum industry are carried out on intervals which are also referred to as overhauls. In terms of levels, this task is also referred to as the maintenance operational level. The main aim of maintenance affairs on the operational level is to develop a cost-effective and adaptable approach to optimise the maintenance schedule. Different techniques have been developed to obtain the best time interval to apply the maintenance policies to avoid a long shutdown.

Robert and Escudero (1983) presented the exact solution of the exact formulation of the scheduling of the plant maintenance personnel which they described as a typical of integer linear programming problem that required large number of variables, equations and inequalities.

Reeves (1993) defined heuristic techniques which seeks good (near-optimal) solutions at a reasonable computational cost without being able to guarantee either feasibility or optimality. He described the types of heuristic methods as: genetic algorithms, taboo search and simulated annealing. These techniques are capable of handling more real-world problem than what a specific algorithm can do and is useful for searching the optimal interval of performing the maintenance. However, there are some drawbacks associated with heuristics techniques, they are:

- The techniques are considered as study of errors (Asadullah and Kundi 2013).
- Heuristics techniques are costly because it requires domain expertise (Nielsen 1994).
- These techniques are not suitable for finding low-priority problems.

Percy and Kobbacy (1997) proposed a rolling horizon approach that "*takes a long-term tentative plan as a basis for a subsequent adaptation, according to information that becomes available on the short term. This yields a dynamic grouping policy that assists the maintenance manager in planning maintenance intervals*".

Duffuaa and Al-Sultan (1999) has classified maintenance planning and scheduling into two major categories. The first category is: scheduled maintenance, which includes preventive and routine maintenance and then scheduled overhauls and corrective maintenance. The second category is unscheduled maintenance or emergency breakdowns. The first category can be planned and scheduled easily, but the second category is stochastic in nature and it causes disruption to the maintenance schedule. They proposed a stochastic programming model for scheduling maintenance personnel. The model maximises the number of completed jobs in a given horizon and minimises the expected reserved manpower and any other shortages. They believed that unlike scheduling in production, the maintenance schedule becomes immediately out of date as soon as an emergency job is received. This necessitates a revision in the schedule and that may create a backlog in the system. They identified the data needed for their model which integrated the deterministic and the stochastic components of the scheduling problem.

Cassady et al (2001) proposed an interesting system structure to optimise maintenance activities on an operational level. They divided systems into subsystems and classified these subsystems further into identical components. Their assumption for each system, subsystem or component was only one of the two states: either they functioned properly or failed. They aimed to select the right maintenance decision for which the alternatives are: minimal repair and replacement of failed or functioning component. Their model was the extension of mathematical programming models.

Saad et al (2004) proposed a mathematical model to obtain an optimal maintenance interval considering the cost of failure of a unit during operation against the cost of planned/preventive maintenance introduced. They calculated the total maintenance cost and in turn to identify an optimum time interval for maintenance activities which is an intelligent mathematical model considering the costs of equipment's maintenance and its reliability.

Krishnasamy et al (2005) implemented risk based maintenance (RBM) methodology which comprised of four modules: Identification of the scope, risk assessment, risk evaluation and maintenance planning. Using this methodology, one is able to estimate risk caused by the unexpected failure as a function of the probability and the consequences of failure. Critical equipment can be identified based on the level of risk and on a pre-selected acceptable level of risk. Maintenance of equipment is prioritised based on the risk, which helps in reducing the overall risk of the plant.

Leou (2006) summarised the generator maintenance scheduling problem which determines the period for which units should be taken offline for planned maintenance over the course of one or two-year in order to minimize the operating cost or increase the system reliability. The most well-known methods that the particular industry of power plants relies on were listed, they are: integer programming, branch-and-bound, decomposition methods, dynamic programming, knowledge-based models, simulated annealing method, probabilistic approach and artificial intelligence method. He introduced the genetic algorithm and simulated annealing method to overcome some of what he said as a short coming of the previous mentioned methods and applied the proposed method to a power plant in Taiwan arriving at the conclusion that this minimum cost solution can be found under a condition of sufficient spinning reserve.

Márquez (2007) suggested that it is possible to solely depend on the recommendations of the manufacturer to plan maintenance actions and interventions if users can justify that these recommendations are appropriate for their operational use. On the other hand, manufacturer is usually unable to anticipate factors such as, issues of consequences of failure, safety considerations, regulatory requirements, availability of resources and unique environmental conditions which require a suitable structure framework to plan and manage maintenance activities.

Khalil et al (2009) created a mathematical approach that takes into consideration the stochastic nature of equipment failures to develop an integrated-cost optimisation maintenance model for industrial equipment, based on a balance between preventive maintenance and corrective maintenance costs. They argued that the behaviour of the system may change considerably for many reasons which can be unrelated to technical issues. They believe that most existing models attempted to use distributions of historical data to represent the system are inconvenient because they could change modes due to reasons that may not directly be related to the machines. In order for them to adopt a mathematical model, they made some assumptions that involved acceptable accuracy in reflecting reality to determine the problem.

Ahmad et al (2011) stated that the most of PM interval is based on experience or original equipment manufacturer (OEM) recommendations. Consequently, the benefits from PM are not fully obtained because the current machine state is not considered. They proposed that mathematical models (also known as maintenance models) are various tools of maintenance management to solve particular maintenance problems.

Cui et al (2013) highlighted that organisations adopt several forms and combinations of maintenance strategies to ensure efficient performance of their facilities. Despite the strategies adopted, there comes a time when the entire facility is shut down for maintenance and project jobs. This is referred to as turnaround maintenance (TAM). The study focused on the managerial skills needed for conducting the TAM perfectly. Their research concluded that, *"It was evident that for TAM project to be managed successfully, appropriate* *management skills are necessary by the team managers (TM) and the TAM management team".*

2.7 Maintenance Framework within the Petroleum Industry

Ahmad et al (2011) stated that Framework (management model) is defined as a guideline, procedure or step-by-step process used to plan or decide for something. The development of a maintenance framework may borrow some ideas from literature and apply some analysis tools from statistical and mathematical theories. Generally, the framework is used to solve particular problems in a systematic way. Therefore, the framework is more practical method to assist engineers and technicians in making decisions. Defining and understanding the problem accurately is the first important step of the proposed model. Their proposed general structure for maintenance constituted from three main steps which are, problem definition, evaluation current machine condition and maintenance decision methods respectively.

Mirghani (2001) proposed a costing framework with the objective of providing reliable, relevant, and timely information about actual costs and the cost efficiency of planned maintenance jobs. The proposed framework includes direct materials, direct labour and support services costs. The traceability criterion is used for assigning direct materials and direct labour costs to planned maintenance jobs. The framework is targeted to serve the estimation of standard costs of a planned maintenance job element by element and in total, reflecting an expected level of cost efficiency and to accumulation of the actual usage of maintenance resources (inputs) at standard prices. In addition to that, facilitating responsibility accounting for maintaining resources and facilitates management by exception by directing management's attention to cost variances that are worthy of their attention, providing a sound basis for the appropriate managerial action(s).

Selvik and Aven (2011) proposed a framework for Reliability and Risk Centered Maintenance (RRCM) and applied it within the offshore oil and gas industry. The main features of the framework are illustrated below (figure 2-3), which shows a process defined by seven boxes of assessments to determine the PM programme. They believe that their framework assists in optimising the preventive maintenance activities by collaborating the conception of RCM and RBM.

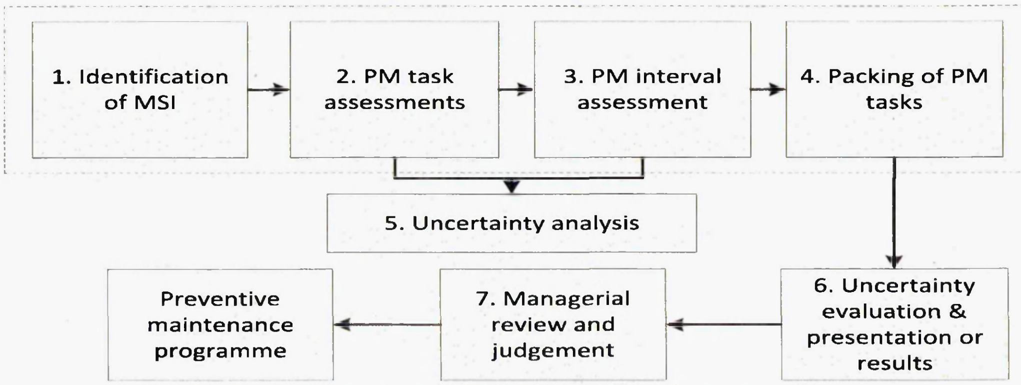


Figure 2-3: RRCM Framework (Selvik and Aven 2011)

Dawotola et al (2012) proposed a maintenance framework for pipeline system based on risk (figure 2-4). Their proposed framework was particularly suitable for repairable systems and for components whose failures are noticeable. The optimisation process inherent in the proposed framework consisted of the following six steps: probability of failure estimation, determination of consequences of failure, estimation of risk of failure, calculation of risk reduction, calculation of total cost function and determination of cost optimal inspection frequency of the pipeline in a preventive maintenance policy.

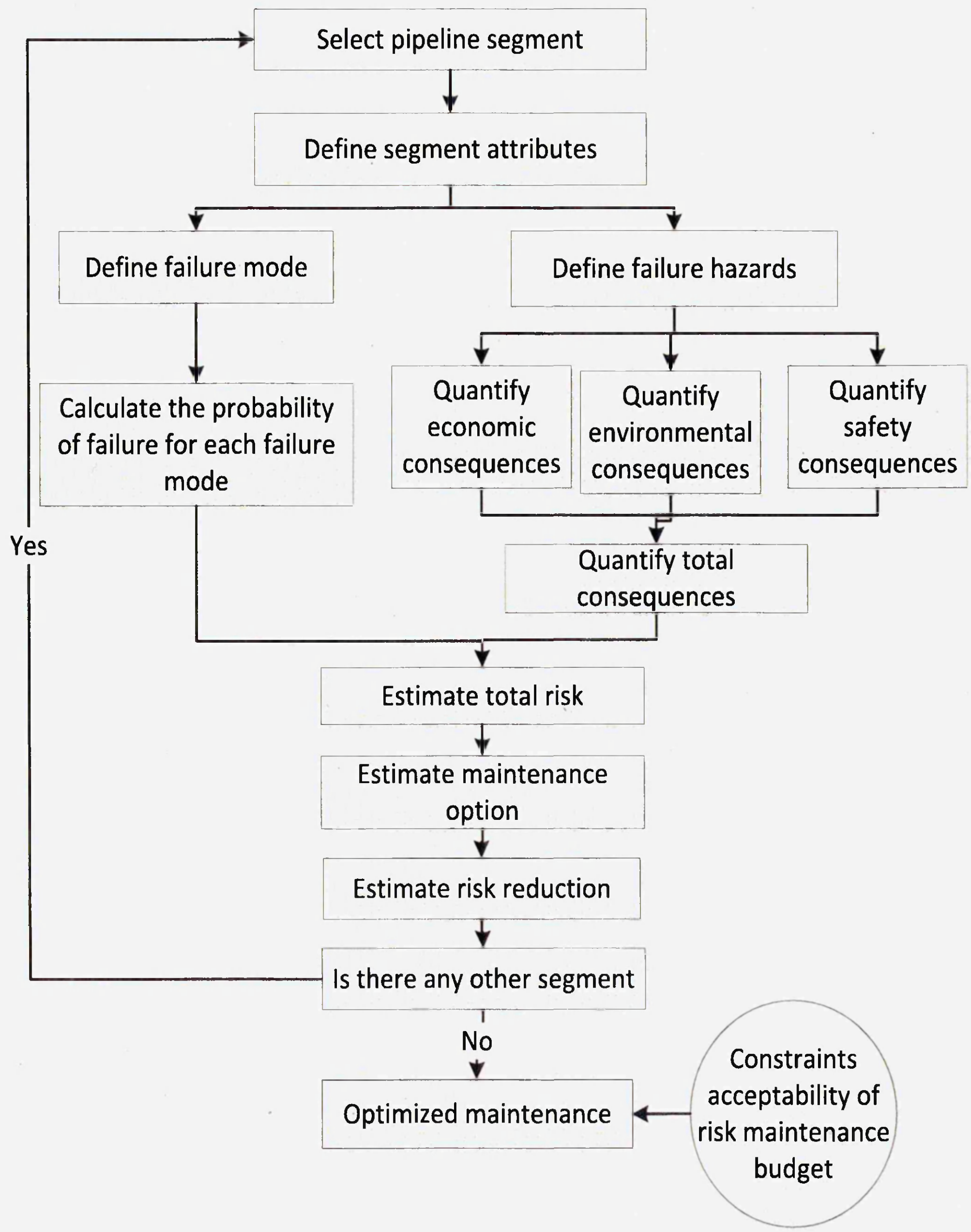


Figure 2-4: Maintenance Framework for a Pipeline System (Dawotola et al 2012)

Jagathy and Deepak (2013) presented a new model, accelerated RCM (A-RCM), to prolong periods of operation without shutdown in the petroleum refineries. The model attempted to avoid the shortcoming of classical RCM by ensuring faster implementation as well as simplifying the process of implementation. They identified the minimum requirement for the new model to follow in order to arrive at preventive maintenance schedules, predictive maintenance recommendations and design changes as:

1. The process should consider the existing maintenance practices and outcomes.
2. All failure modes that are reasonably likely to occur must be considered.
3. Critical equipment needs more intensive analysis.
4. The model should provide results quickly.
5. The results should be measurable at a macro-level.
6. The new model should integrate with the existing practices.

They suggested that the A-RCM model and process provide refineries with a comprehensive tool for accelerated improvement in reliability.

This section covered some of the most important maintenance frameworks that are implemented within the petroleum industry. The next section deals with the inventory management and spare parts control.

2.8 Inventory Management and Spare Part Control

Inventories can be described as goods or materials which are kept for a time, to be used only when they are needed either during an operational process or for the fulfilment of a customer demand (Krajewski et al, 2012). According to Drury (2013) inventory refers to materials kept in stock which are used to fulfil and meet any future demands of consumers.

Inventory management has become an important focus area for researchers due to the development of production processes and the increasing demand for spare parts (Jingjiang and Zhendong 2012). Spare parts inventory management plays an essential role in determining the level of inventory and operation of the equipment, not to mention the proportion of returns while reducing the risk of recession stock.

Keth, et al (1994) stated that the basic pre-requisite for the successful management of inventory relies on the management considering three important issues, which are:

- The certainty of whether a part to be stocked or not. Whether the purchase order should be released.
- The quantity which should be requested.

This was supported by Bošnjaković (2010), who believed that the quantity to be retained should also be determined for the successful management of inventory.

The management of maintenance of spare parts is not an easy task, as keeping too much inventory can have an effect on the business's cash flow. On the other hand, failure to provide the required quantity at the right time may have a huge negative impact on all the operational processes (Aronis et al 2004). Although the goals of reducing inventory and the availability of spare parts appear to be two inverse targets, by using an advanced inventory management and a specialised information system, it is possible to accomplish this goal.

Hua et al. (2007) pointed out certain properties and needs which makes spare parts management vary from other types of inventory at several points:

- A high quality of service is required as a lack of spare parts could result in significant financial loss. Indeed, as spare parts demand can be very intermittent and complicated to predict, it is essential to keep a very large number of items in stock, with the cost of such items often at a high price.

- The unavailability of historical data regarding spare parts demand is another challenge which can make demand forecasting difficult.

The main aim of any inventory management system is to attain sufficient service level whilst minimising the inventory investment and administrative costs. This essentially means that the inventory management should aim at striking equilibrium between costs, which results from the acquisitions, and retention of the required spare parts inventory and consideration of the availability of the inventory. In addition to that, purchasing cost, item cost and holding cost must also be considered, as much as operation shutdown cost is considered (Bevilacqua et al 2008).

Liao and Rausch (2010) highlighted that in order to successfully manage and control the manufacturing process, management should be able to forecast and prevent process breakdown.

Schroeder et al (2011) stated that certain authors have indicated some important factors when it comes to inventory management such as: the demand for spare parts associated with preventive maintenance may be specific to a certain extent. The demand for majority of the items will be unpredictable and unsteady. The decline in the age of goods during their life cycle and the complexities of the production processes will lead to an increased risk of obsolescence for certain items, as well as the addition of new items to the inventory.

2.8.1 Inventory Cost

Inventory cost is the most important and decisive factor when it comes to determining inventory level and the reordering point. The inventory cost can be further be broken down into four sections as shown below (Evans, 1997). Syntetos (2009) reasoned the importance of controlling inventory to the cost associated with the retention of stock.

The inventory cost can be classified into four types - unite price, ordering cost, holding cost and stock-out cost. The criticality reflects how the potential unavailability affects the safety of the people and environment, the costs of downtime and the quality of the processes (Aronis et al, 2008).

2.8.1.1 Unit Cost

This can be defined as the amount of money a company needs to pay to suppliers in order to acquire a product or a spare part. While Evans (1997) believed that the majority of product prices can remain invariable, Waters (2008) argued that comparing item price can be very difficult as each vendor offer will differ from the other in terms of price, quantity discount, delivery, payment method and so on.

2.8.1.2 Ordering Cost

This includes all costs associated with the purchase order, irrespective of the amount ordered. It comprises of the cost and time spent on generating and sending the purchase request, evaluating supplier quotations, expediting and following up shipments, transportation expenditure, receiving and inspecting orders and payment procedure costs.

2.8.1.3 Holding Cost

It takes into account all the charges associated with storing items and includes all warehouse operation activity expenses such as: handling materials, picking and packing items, monitoring inventory level, the cost of operating and maintaining warehouse equipment and insurance.

2.8.2 Economic Order Quantity (EOQ)

Waters (2008) stated that *"because of the ease of application, its capability to be used as a guide in many different situations, and its flexibility, the use of EOQ is widely encouraged".* According to Heizer and Render (2014) the EOQ model (equation 2-6) is a well-known technique used to control independent demand but it based on a number of assumptions.

$$\mathrm{EOQ} = \sqrt{\frac{2DOc}{Hc}} \qquad 2\text{-}6$$

Where:-

D Demand.

Oc Order cost for each order.

Hc Holding cost for each item yearly.

2.8.2.1 Reordering Point (ROP)

One of the basic principles of inventory management is when a new purchase order should be released, in a simple inventory system, where the demand and the lead time are constant. This can be determined by multiplying the daily demand by lead time (Heizer and Render 2014). However, in reality, demand and lead time are not always invariable due to uncertain demands and lead time. Therefore, organisations must retain more units to be used in combating any unexpected demand or overdue shipments; a process also known as safety stock.

2.8.3 Safety Stock

Safety stock (SS) can be defined as the quantity of stock which is preserved in order to protect against the demand uncertainty (Reid and Sanders 2005). Thus, this stock can be used if the demand is higher than expected or the replenishment cycle takes more time than expected (Bowersox et al 2013).

2.8.4 Probabilistic Model and Safety Stock

Heizer and Render (2014) defined three different probability models which can be implemented to calculate the ROP.

2.8.4.1 Variable Demand and Constant Lead Time

$$ROP = (A_{VD} \times L_T) + Z \times \alpha_d \quad \text{2-7}$$

Where:

A_{VD} Average demand during lead time.

L_T Lead time.

Z Number of standard deviations.

α_d Standard deviations of demand during lead time.

2.8.4.2 Constant Demand and Variable Lead Time

$$ROP = (D_d \times A_{VLT}) + Z + D_d \times \alpha_{LT} \quad \text{2-8}$$

Where:

D_d Daily demand.

A_{VLT} Average lead time in days.

α_{LT} Standard deviations lead time in days.

Z Number of standard deviations.

2.8.4.3 Variable Demand and Lead Time

$$ROP = (A_{VD} \times A_{VLT}) + Z \times \alpha_{LT} \quad \text{2-9}$$

2.8.5 Spare Parts Classification

Gopalakrishnan and Banerji (2013) defined spare parts as a part which is similar to the one which must be replaced because of wear and tear sustained during the operating life of the equipment. Classification of items is very important when it comes to helping management identify important items and facilitating the demand forecasting process and inventory control (Bacchetti and Saccani 2012). Determining the level of spare parts inventory primarily depends on the classification of spare parts (Jingjiang and Zhendong 2012). In addition to that, Millstein et al (2014) believed that inventory performance can be managed and observed more effectively if inventory strategies fit best within a group of items instead of each individual item.

ABC classifications developed by General Electrical in the 1950s to control their inventory is one of the most used classifications based on cost criteria (Guvenir and Erel 1998). ABC classification is a well-known approach and it has been used widely in many different industries (Ramanathan, 2006; Molenaers et al 2012). Keskin and Ozkan (2012) stated that in order to apply this method, items should be annually arranged in descending order with regard to money usage and then calculated by multiplying the item price by the annual demand.

VED analysis is another recognized spare part classification that is based on the criticality of an item. "V" stands for vital items without which a hospital cannot function, "E" for essential items without which an institution may function but it can affect the quality of the services and "D" stands for desirable items, unavailability of which will not interfere with the functioning (Gupta et al 2007).

2.8.6 The Role of Spare Parts Inventory in Oil Industrials

Oil and gas industry usually rely on very expensive equipment and the consequences of downtime are very costly which may require immediate maintenance. The system downtime period will be longer if a critical spare part is not available, and thus managing these parts becomes a principal task when it comes to ensuring sustainability in their operation and reducing downtime for such equipment (Louit et al 2011). In order to stay competitive, companies must also find new ways to make the most out of their assets. Therefore, ensuring uptime and safety, mitigating risks and reducing costs are considered essential for equipment availability and maintenance (Thakur 2014). A sufficient quantity of spare parts is vital when it comes to supporting and strengthening the operational capacity of the production equipment, although keeping too much inventory does not eliminate the risk of equipment failure. In order to maximise production without prejudice to the safety of operating, oil and gas companies must ensure the long-term integrity of their equipment.

2.8.7 Spare Parts Inventory Features

Spare parts can be divided into two categories, which are: repairable and non-repairable parts. Repairable parts are parts those that can be swapped into new ones and sent to a repair centre, so these parts are technically and economically repairable (Hadi-Vencheha and Mohamadghasemi, 2011). On the other hand, non-repairable parts are those which are not technically or economically repairable, in a failed situation, these defective parts well be replaced by a new one and scrapped (Driessen et al, 2014).

Spare parts represent one of the fundamental elements when it comes to supporting the maintenance process. Determining the demand for spare parts is an essential key for supporting and strengthening the operational capacity of the production equipment (Hu et al,2013). Additionally, the unavailability of spare parts can have a negative impact on operational performance, while the cost associated with critical purchase orders is also very high (Liao and Rausch, 2010). The importance of spare parts inventory stems from its direct role in determining the level of inventory and operation of the equipment and the proportion of revenues as well as the risk of obsolete stock (Chen et al, 2010).

2.8.8 Spare Parts Demand

Spare parts inventory differs from other industrialised inventories in a number of ways. The role of spare parts inventories is to keep equipment in an effective condition. The policies which dictate the level of spare parts inventories will be impacted by the function of equipment, the equipment's condition and the type of maintenance required (Kennedy et al, 2002).

(Chu et al, 2008) believed that managing enormous spare part inventories with equivalent attentiveness cannot be accomplished. Whilst extra inventory is objectionable from a management viewpoint, in contrast, not stocking a sufficient number of spare parts at the right time may lead to a malfunction in the production process, as well as result in loss of revenue and significant costs.

One of the main requirements when it comes to successful spare parts inventory management is accurate demand forecasting (Vasumathi and Saradha, 2013). The challenges faced by management relate to the inability of traditional forecasting methods to provide an accurate categorization of demand (Porras and Dekker, 2008). This is due to the fact that usage of spare parts is often irregular. If the cost of failure associated with not keeping certain parts is too high, this could result in an increase in the amount of stored spare parts (Scala et al, 2014). The nature and features of spare parts demand, such as unpredicted demand, obsolete items, slow moving and risk cost cannot be easily calculated as handling such inventory can be very complex and difficult (Wahba et al, 2012).

2.8.9 Integrated Spare Parts and Preventive Maintenance Models

Maintenance relies heavily on the availability of spare parts to reduce the equipment downtime and to allow the system to perform its anticipated functions (Luxhøj et al, 1997). Destombes et al (2009) emphasizes on the importance of spare parts demand and their connection to maintenance requirements.

Kaio and Osaki (1981) examined the situation where spares inventory ordering policy and replacement age are jointly optimised. The proposed model was built into two main assumptions, which are, the original unit, in which a spare part is replaced after delivery even if the original is still operating and the second assumption that the spare part is put into an inventory until the original unit fails. Their work ignored the importance of trade-off between maintenance-related costs and inventory-related costs.

Kabir and Al-Olayan (1994, 1996) further extended the analysis to the case of multiple units in service and the possibility of holding more than a single unit of inventory and emphasised on the importance of considering the relation between the spare part and time aged maintenance.

Chelbi and Daoud (2001) discussed an optimal periodic replacement and spare parts provisioning strategy. The proposed strategy was completely defined once the replacement period (T), the replenishment cycle (R) and the ordering point *were* determined (S). The optimal strategy (T, R *and* S) aimed to minimise the total expected cost (replenishment cost of spare parts inventory management cost) per unit over an infinite span of time. A computation procedure was proposed to generate from the mathematical model, the optimal preventive replacement period and the optimal spare equipment threshold level.

Vaughan (2005) stated the importance of spare parts for plant and equipment and their expensive cost to keep in inventory as well as the imperative availability of spare parts for the maintenance when needed, in order to avoid costly plant shutdown or equipment unavailability. A dynamic programming characterization was presented for a spare parts ordering policy. The model investigated that demand for spare parts arises from two sources, random failure of units in service and bulk replacement at regularly scheduled preventive maintenance intervals.

Liao and Rausch (2010) stated that although both condition based maintenance (CBM) and spare part inventory control have been studied extensively, their integration has not been studied well. They proposed a joint production and spare part inventory control strategy driven by CBM for a piece of manufacturing equipment with a critical unit. The first stage minimizes the base-stock level "S" that satisfies the specified stock-out probability and the resulting base-stock level is then used as a known quantity in the second stage, to determine the optimal preventive maintenance. They believe that the proposed joint decision-making strategy should be able to significantly reduce the total operating-cost in today's production processes as a new spare part inventory control and production paradigm driven by condition based maintenance.

Van Horenbeek et al (2013) reviewed relevant work and classified them based on the combination of maintenance policy (block-based, age-based, and condition-based) and inventory policy (periodic review and continuous review). Jiang et al (2015) stated that maintenance is the main source of spare parts consumption and spare parts are the pre-condition for performing maintenance. They explained that conducting too frequent maintenance may result in more spares consumption, but less maintenance may increase the risk of system downtime.

On the other hand, the shortage of spares postpones the maintenance procedures and may increase equipment downtime but excess of spares involves extra expenditures. They emphasised on the importance of determining the frequency of maintenance, the ordering time and the quantity of spare parts. They classified joint optimisation models into simulation models and mathematical programming models and criticized the simulation models for being random and each round of simulation generates a different process. They proposed joint optimisation model of block replacement and periodic review inventory policies for a multi-unit system under the influence of deteriorating inventory. The model considered the lead time to be constant and to choose the reorder points at equidistant points in time to bring the inventory level up to the maximum inventory level.

2.9 Risk Assessment

According to the British Standard Institute (BSI 2000) risk is the "uncertainty inherent in plans and the possibility of something happening that can affect the prospects of achieving business or projects goals".

Reynolds (1996) stated that risk assessment may be quantitative or qualitative in nature. Quantitative risk assessment is done by the estimation of frequency and its consequences. Quantified risk assessment is only appropriate where it is reasonable and practicable. Reasonable in terms of the cost (it should not be high compared with the value of solving the problem) and practicable in terms of the availability of information and data (Carter et al, 2003).

ISO (2009) defined the risk assessment process as the overall process of risk identification, risk analysis and risk evaluation. Dawotola et al (2012) defined risk as "the considered expected loss or damage associated with the occurrence of a possible undesired event".

Tixier et al (2002) identified 62 methodologies for risk analysis and assessment and separated these methods into three different phases (identification, evaluation and hierarchisation). These methodologies were further classified in terms of input data into seven different classes (plan or diagram, process and reaction, products, probability and frequency, policy, environment, text, and historical knowledge). The methods were then ranked into six classes based on the combination of four usual criteria (qualitative, quantitative, deterministic and probabilistic) and finally, the output data is classified into four classes (management, list, probabilistic and hierarchisation).The shortages of the mentioned methods were identified and the most important feature of the shortages was identified as, more general the methodology is, the less it takes into account the specificities of the studied case, and on the contrary, if the methodology is too specific it will be less transposable to another case.

IPCS (2004) believes that risk assessment is the first component of risk analysis and it is a process that comprises of four main steps: Identification of hazards, hazards characterization, exposure assessment and risk characterization.

Maylor (2010) stated that the majority of risk management activities rely on qualitative data which is obtained based on people's perceptions of risk levels. The qualitative data can be presented on a grid with two axes: probability and impact (Low, medium and High). The qualitative risk assessment process is considered to be comparable to the quantitative risk assessment process.

Merna and Al-Thani (2011) believed that the quantitative approach of risk assessment tends to locate absolute value ranges together with probability distribution for the outcome and therefore, involves more sophisticated analysis facilitated by the use of computers.

Yoe (2011) defined risk assessment as the process of estimating (evaluating) the risks associated with different expected hazards, opportunities to gain risk management options. The reason for involving "opportunities" falls under the belief that if opportunities are not recognised, this situation is going to be considered as a loss. He divided risk assessment into two main types: qualitative and quantitative. Qualitative risk assessment is characterised by its lack of dependency on the numerical expressions, this implies that the qualitative risk assessment approach relies on risk characterizations or classifying risks into descriptive categories such as high, medium and low.

2.9.1 The Importance of Risk Assessment within Petroleum Industry

Petroleum industry is one of the industries that is considered to be associated with hazardous and high risk due to the fact that there are a considerable amount of flammable, toxic and explosive substances being processed and stored within the facility. Risk assessment, therefore, becomes vital and necessary for all the equipment and components of the petroleum industry.

Khan et al (2001) defined the science of risk assessment (RA), which has emerged in recent years with ever-increasing importance as a process that includes both qualitative and quantitative determination of risks and their social evaluation. The key aspects of accidents in chemical process industries which addressed within RA were mentioned as:

a) Forecast of accidents: This is aimed at creating opportunities to rectify problems before any harm can occur.
b) Consequences analysis of likely accidents.
c) Development of managerial strategies for "emergency preparedness" and "damage minimization."

Griggs (2011) stated that one of the worst catastrophic disasters in the US history was the blowout of British Petroleum (BP)'s Macondo well in the Gulf of Mexico which took place on April 20, 2010. As a result of this 11 people were killed, while several others were severely injured. It also affected the livelihoods of many fishermen as well as many marine animals were also destroyed in the tragedy.

RPS Group (2011) stated that over the last three decades there have been a considerable number of catastrophic accidents occurring every 2-3 years on an average, associated with the petroleum offshore operations. Therefore, the assessment of risks with the petroleum industry is vital in order to mitigate the risks and create a safe environment.

Ambituuni et al (2015) indicated the importance of the risk assessment within the petroleum sector and reported that accidents involving transportation of petroleum products by road have been associated with high frequency of occurrence and high safety consequences in developing countries. Using Nigeria as case example, 2318 accidents approximately were analyzed involving truck tankers from 2007 to 2012 with a tailored risk assessment framework.

2.9.2 Risk Assessment within Petroleum Industry

There are different risk-based approaches reported in literature ranging from the purely qualitative to the highly quantitative methods. Many authors have used probabilistic risk assessment (PRA) as a tool for maintenance prioritization.

Arendt (1990) proposed that risk assessment approach integrates reliability and consequence analysis, and attempts to answer the following questions in order to assess the risk:

- What can go wrong?
- How can it go wrong?
- How likely is its occurrence?
- What would be the consequences?

Balkey and Art (1998) developed a methodology, which includes risk-based ranking methods, beginning with the use of plant PRA for the determination of risk-significant and less risk-significant components for inspection and the determination of similar populations for pump and valve in-service testing. This methodology integrates non-destructive examination data, structural reliability/risk assessment results, PRA results, failure data and expert opinions.

Khan and Abbasi (1998) proposed a methodology for risk assessment named Optimal Risk Analysis (ORA). ORA involved four steps: hazard identification and screening, hazard assessment (both qualitative and probabilistic), quantification of hazards or consequence analysis and risk estimation (figure 2-5).

Different techniques such as hazard and identification and ranking analysis (HIRA), hazard analysis and operability (HAZOP) and probabilistic hazard assessment were used for each step.

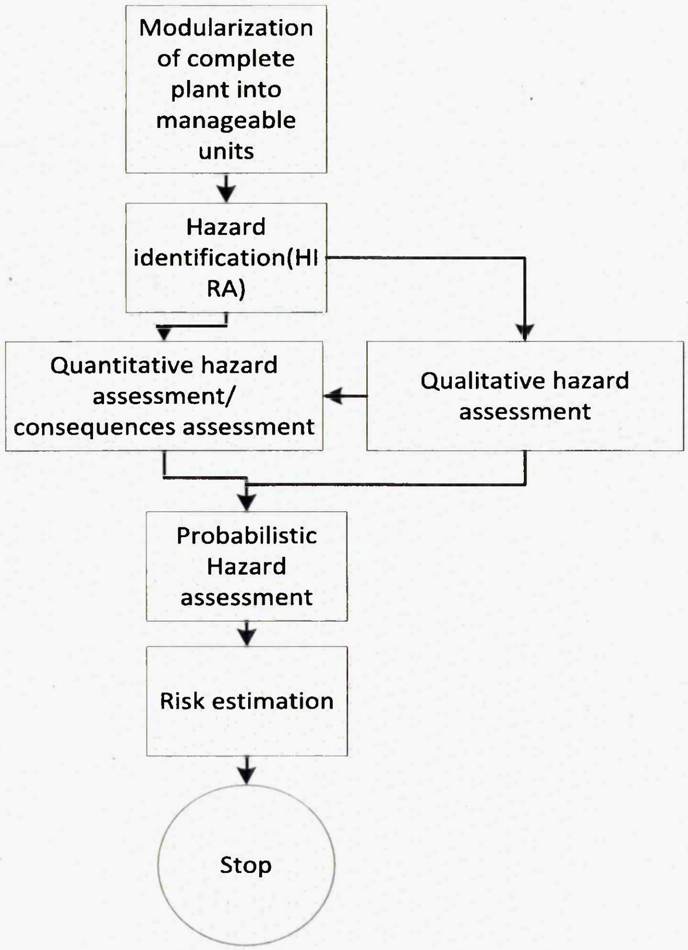


Figure 2-5: Simplified Block of Optimal Risk Analysis (Khan And Abbasi 1998)

Culp (2002) suggested that petroleum industry embraces a conventional undifferentiated risk management approach which can be categorized into three main sequential stages:

1. Risk Analysis: Which is the stage when risky events are identified.
2. Risk Assessment: In this stage, the frequency and consequences of the previously identified risks are determined.
3. Risk control: In this phase, risk is managed by selecting the right procedure.

Khan et al (2001) demonstrated the applicability of a new risk assessment methodology ORA (optimal risk analysis) in conducting risk assessment of a typical petrochemical industry. ORA aimed to reduce the costs and time required by conventional risk assessment methodologies, without compromising on the desired level of accuracy and precision. Domino effect analysis (DEA) procedure was proposed to forecast accidents and their impacts.

Out of the two main phases of risk-based maintenance, Arunraj and Maiti (2007) described the importance of the risk assessment as the critical and foremost important phase, as the maintenance decisions are going to be made with the assessed risk as centre. The proposed risk assessment involves identifying potential threats, estimating their likelihood (number of events/time interval), and estimating the consequences (impact/event). The combination of these estimates represents the risk (impacts/time interval) associated with the activity being evaluated.

Bertolini et al (2009) reported the application of the risk-based inspection and maintenance (RBI&M) method to two specific stages in the maintenance activities of the refineries. The panel of experts developed heuristic methods in order to apply RBI&M procedure to the two cases allowing the refinery to minimize the overall risk taking into consideration the limits in terms of time and budget (in turnaround case) and of human resources (in the management of work orders). One of the main steps of the proposed RBI&M was the risk analysis and assessment which was built mainly on three factors (probability, exposure and consequences) to determine the overall risk.

Cigolini and Rossi (2010) identified different stages in petroleum supply chain in terms of safety equipment, operational risks, plants and processes and agreed that no specific risk management approach has been dedicated for each specific stage. They stated that the most popular forward techniques in petroleum industry to assess the risk are:

1. The Hazard Checklist: This technique is based on performing plant analysis to verify whether risky events identified in previous risk analysis or other similar plants could occur.
2. Event Three Analysis (ETA): This technique facilitates the ability to determine the consequences of a potential risk based on safety equipment and procedures adopted in the plant.
3. Fault Three Analysis (FTA): This technique helps in risk identification process by associating the consequences to the primary risky events.

Anvaripour et al (2013) suggested that the assessment of risk (R) considered for each asset was: $R = F \times C$

Where: F is the frequency factor or number of failures in a certain time period (year) and C is a consequence of the failure measured as follows:

$$C = (O_I \times O_F) + M_C + I_{SE} \qquad 2\text{-}10$$

Where:

O_I Operational Impact factor.

O_F Operational Flexibility factor.

M_C Maintenance Cost factor.

I_{SE} Impact on Safety and Environmental factor.

The classifications of scales for ranking the different assets were established as follows:

- The failure frequency scales (F) were classified from 1 to 4, according to the number of failure occurrence per year.
- The five scales assigned to operational impact (OI) range from immediate plant shutdown to no significant impact on operations.
- The maintenance cost (MC) factor was classified into three scales.
- Six scales were allocated to impact on safety and environment (ISE) with respect to the magnitude of impact on the safety and environment.

Hauge et al (2015) characterised the uncertainties associated with the risk assessments and some of the surrounding debates. The study arrived at the conclusion that all aspects of risks should be considered when it comes to uncertainty. They explained the implications of the uncertainties including the:

1. Potential values embedded in the risk assessments.
2. Lack of validity of quantified worst-case scenarios and their probabilities and impacts.
3. Limited prospects of filling addressed knowledge gaps.
4. How risk assessments restrict the debate on what issues and uncertainties are considered relevant.

The assessment of the risk within the petroleum industry is an essential activity due to the importance of the activity in terms of preventing the occurrence of the risk and adding value to the system by improving the reliability of the system.

2.10 Conclusion and the Knowledge Gap

Chapter Two covered the literature review of topics related to maintenance in general and of the petroleum industry in particular. The chapter covered the aspects of the strategies that were implemented to select the maintenance policies based on reliability and risk. Some work has been presented with regards to the use of AHP for the selection of the maintenance policies within the petroleum industry (Section 2.5). The literature shows that there is no general framework for the selection of maintenance policies, but instead the proposed AHP frameworks were targeting a specific sector and equipment, most of which was for pipelines.

The operational level was covered within the literature (Section 2.6) and some work has been presented to attempt to schedule the activities of the preventive maintenance within different fields and within the petroleum industry. However the existed mathematical models do not take into account the major maintenance costs which related to the nature of the petroleum industry.

The inventory management and spare parts control was outlined in section (2.8) and some of the integrated spare part and PM models were highlighted to optimise the movement of spare parts. However, most of the models did not utilize the optimised time of maintenance interval and connect it to the spare part leading time.

The risk assessment within the petroleum industry is a major activity to ensure avoidance of undesirable activities. Qualitative and quantitative methods were demonstrated in section 2.9 to assess the likelihood of the risks involved and their possible consequences. Due to the importance of risk assessment, further investigation is necessary to look into the possibility to improving the assessment method of the likelihood of the occurrence of the failure and enhancing the existing methods of estimating the consequences.

In order to bridge the identifiable gaps, an integrated framework is proposed to manage the major maintenance activities within the petroleum industry (Chapter Three). The framework consists of four major activities. Generic AHP model is presented to identify the criteria, sub-criteria and alternatives that lead to the optimum selection of the most suitable maintenance policy (Chapter Four). Proposed mathematical model is presented to contain all the major related costs of maintenance for the petroleum equipment to arrive at the identification of the optimum intervals (Chapter Five). An integrated approach between preventive maintenance and spare parts control is proposed in Chapter Six. A proposed model for the assessment of the risk within the oil and gas industry is demonstrated in Chapter Seven to enhance the safety reliability of the system.

Chapter Three

Research Methodologies and the Proposed Integrated Maintenance Framework

Chapter Three will be covering the various methods that will be applied to optimise each major activity and is divided into two main sections. The first section covers concisely each selected methodology for the optimisation of a certain activity. The second part covers the proposed integrated maintenance framework.

3.1 Introduction

The challenges associated with the maintenance in general and specifically within the petroleum industry were introduced in the literature review in Chapter Two. Different strategies are available for maintenance management to assign the most suitable maintenance policies either based on the importance of reliability or risk. Different approaches and models are also available to select the time of carrying out the maintenance activities (maintenance interval).

The challenge of assessing risk in terms of likelihood and consequences has been given considerable time by researches and different techniques (qualitative and quantitative) were discussed with the literature review. Inventory management is another aspect of concern within the petroleum companies, as the spare parts of some of the equipment is very expensive and running out of stock leads to the disturbance of the operations of maintenance and consequentially stopping the entire production line.

In order to optimise major maintenance activates, the main objectives of maintenance have to be identified and maintenance has to be defined as a function that crosses to other departments to enhance the efficiency of the entire operation system. To bridge the gap between the current status of maintenance performance and the expected vision to improve the maintenance function, a guiding principle that covers the major activities of maintenance is required (Márquez, 2007).

3.2 Research Methodologies

To optimise the maintenance activities within the petroleum industry, an integrated framework is proposed in this study. The framework links the major activities associated with maintenance within the petroleum industry and each of these activities are further optimised in order to add value to the optimisation of the entire framework. Four main activities have been identified within the scope of maintenance:

- Maintenance strategic level.
- Maintenance operational level.
- Inventory management.
- Risk assessment within the petroleum industry.

3.2.1 Maintenance Strategic Level

On this level, the focus is to decide on the selection of the most appropriate policy for equipment maintenance. In other words, the question that needs to be answered on this level is what policy should be assigned into equipment or its parts. Deciding on the most appropriate policy for equipment maintenance within the petroleum industry is a sophisticated matter, since the maintenance program must combine technical requirement with firm's managerial strategy. The technical aspect can generally be summed up in having healthy equipment and the managerial aspect is generally concerned with having the production running smoothly so the necessity of the availability of equipment.

Different approaches have been developed and discussed extensively within the literature review which can be summarized into the following:

- Reliability Centered Maintenance (RCM).
- Risk Based Maintenance (RBM).

Each method has its own techniques and advantages. However, in a multi equipment industry, such as the petroleum production line, reliability, availability and risk vary from upstream, midstream and downstream stages and it also differs from one equipment to another. This variation requires a multi criteria decision making (MCDM) technique in order to ensure the selection of the most appropriate maintenance policy.

Wang et al (2007) suggested that plants are equipped with various machines, which have different reliability requirements, safety levels and failure effect. Therefore, it is obvious that an appropriate maintenance program must define different maintenance strategies for various types of machines which will lead to an acceptable level of reliability, availability of production facilities and avoid unnecessary investment in maintenance. One of the most outstanding MCDM approaches is the Analytic Hierarchy Process (AHP) (Torfi et al, 2010). In this research, classical and fuzzy AHP are applied to optimise the selection of maintenance policies at strategic level for equipment within the petroleum industry.

Figure (3-1) presents the proposed steps to be followed in order to arrive at the selection of the alternatives (maintenance policies). A broad explanation of each of the steps is covered in chapter 4. However, the main steps for classical and fuzzy AHP are listed as followed:

3.2.1.1 Building the Hierarchy Structure

In this step, the decomposition of the entire problem is constructed. Identifications of the main criteria that influence the selection of the maintenance policy, sub-criteria impact on each of the main criteria and of alternatives (possible maintenance policies) are established in this step.

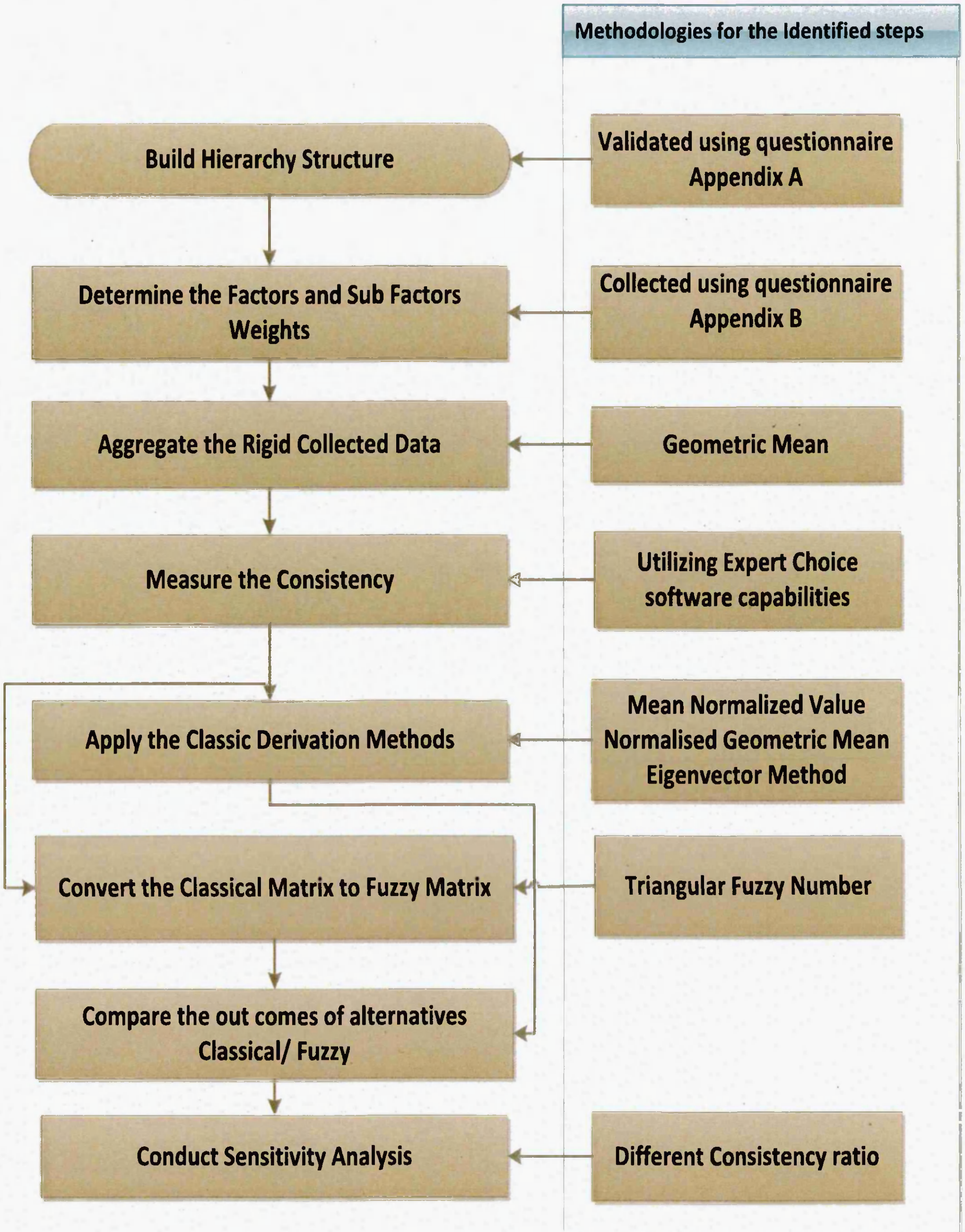


Figure 3-1: Steps of Selection of the Maintenance Policies

3.2.1.2 Collection of the Data

After building the hierarchy structure, a pairwise comparison is set to obtain the preference between each two nodes with respect to the higher node. A questionnaire (Appendix B) was sent out targeting academics and industries to fill in the pairwise comparison.

3.2.1.3 Aggregation of the Collected Data

Once the data from the questionnaire are collected, the geometric mean is used to aggregate the collected data.

3.2.1.4 Building the Comparison Matrix

Different comparison scales are available to translate the linguistic preference to numbers to build the matrix. The scale is identified while building the questionnaire to the advantage of the correct scale preference. Each matrix represents the pairwise comparison between certain factors with respect to the upper node

3.2.1.5 Consistency

In this step, the consistency of each matrix is measured. Once the weights have been allocated for each criterion and recorded, a consistency check has to be performed.

3.2.1.6 Pairwise Matrix Evaluation Methods

Different derivation methods of the matrix are available for the classic AHP. In this work three methods will be applied and compared to each other:-

- Mean of the Normalised values (MNV).
- Normalised Geometric Mean (NGM).
- Eigenvector Mean (EVM).

3.2.1.7 Sensitivity Analysis

The purpose of this analysis is to study the reflection of the changes in the preference between the criteria and sub-criteria onto the prioritization of the alternatives (maintenance policies).

3.2.1.8 Fuzzy AHP

The reason of applying FAHP is that the use of fuzzy logic represents the uncertainty in the translations of expert's judgment. It follows almost the same steps of AHP as above, but the difference is to use the triangular fuzzy number (TFN) scale either to translate the linguistic preferences or to convert the rigid numbers into fuzzy values.

Applying AHP and its different derivation methods and fuzzy AHP using the TFN scale is expected to provide the maintenance team on the strategic level with the method of selecting the most appropriate maintenance policy within the petroleum industry.

3.2.2 Maintenance Operational Level

Once the most appropriate maintenance policy is assigned to the equipment/parts, the maintenance team moves to another task which is the determination of the most optimum time for maintenance intervals. The operational level, deals with the problem associated with the optimum time to perform preventive maintenance.

Different techniques have been developed to obtain the best time interval to perform preventive maintenance, to avoid a long shutdown or short mean time between maintenance, which were discussed in the literature review.

In this study, development of total maintenance cost is proposed and all major relevant costs for both corrective and preventive actions are identified for the petroleum industry to optimally select the most suitable maintenance interval.

The proposed mathematical model is built mainly on the following:

- Identifying the associated costs in case of the occurrence of unplanned maintenance where corrective actions are required.
- Identifying the costs associated with the preventive actions.
- Calculating the probability of failure which will be later multiplied by the identified corrective costs.
- Calculating the survival factor and multiplying it with the preventive costs.

Figure (2-3) demonstrates the hierarchy of the proposed model which will be extensively demonstrated in Chapter 5.

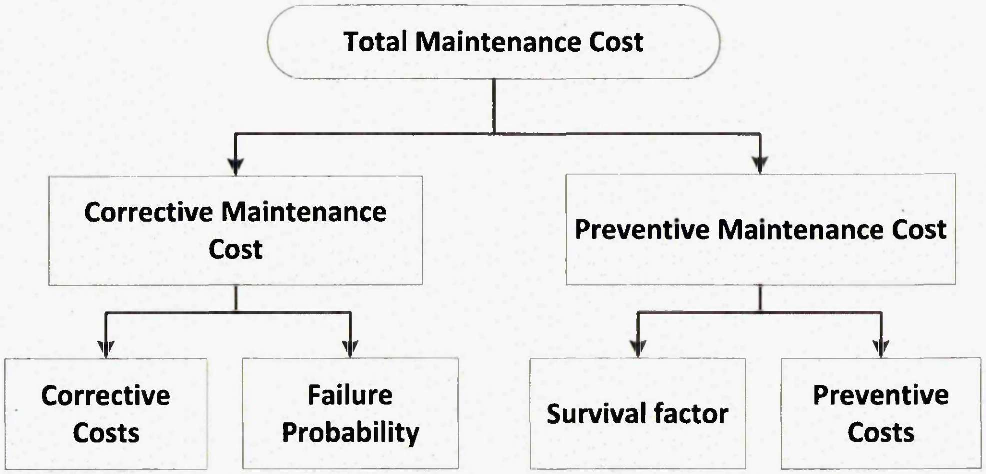


Figure 3-2: The Hierarchy of the Proposed Mathematical Model

3.2.3 Inventory Management

Within the identification of the associated costs of maintenance, spare parts are estimated to have a high portion of maintenance's cost, which leads to the conception of the necessity of optimising this major activity within petroleum companies. The role of spare parts inventories is to keep equipment in an effective condition. Spare parts represent one of the fundamental elements when it comes to supporting the maintenance process. As such, determining the demand for spare parts is the key in supporting and strengthening the operational capacity of the production equipment. The system downtime period will be longer if a critical spare part is not available and thus, the management of these parts has become a principal task in terms of sustaining their operation and reducing downtime for such equipment.

Maintenance as a function has to impact positively on the inventory management or the management of spare parts. The optimisation of spare parts is important so that the maintenance will have the required parts for the maintenance interval and simultaneously avoiding the over stock of spare parts, which influence negatively on inventory department and the entire company.

The intended methodology for optimising the spare parts is to evolve an integrated approach between maintenance requirements and spare parts inventory to find a mechanism, which can help in determining the required quantities of spare parts, as well as the compulsory time limit.

The majority of the maintenance activities within the petroleum industry are conducted preventively based on time. Therefore, the proposed integrated method for optimising the spare parts is to optimise the preventive maintenance intervals and linking it to the inventory department, which will be broadly discussed in Chapter 6.

3.2.4 Risk Assessment

The operational activities in oil and gas industry comprises of many hazardous scenarios and risky events associated with them. The production line with oil and gas industries store and process a large amount of flammable and explosive materials, which in return could lead to environmental disasters, human fatalities, injuries and losses in production and assets. Therefore, risk assessment management support the decision-makers to manage these risks and also take proper actions to reduce and mitigate them.

As part of the integrated maintenance framework to optimise the maintenance activities and because the nature of the petroleum industry enforces the need for identifying convenient way of estimating the risk that may occur as consequences of the failure, a quantitative and qualitative model is proposed.

Khan and Haddara (2003) identified four impacted areas as consequences of the failure occurs which are:

- System performance loss.
- Financial loss.
- Human health loss.
- Environment loss.

A mathematical model is presented in Chapter 7 to estimate the likelihood of risk. The consequences of the risks are assessed in the four above-mentioned areas. The system performance loss is assessed using the scheme for system performance function. A mathematical presentation has also been proposed to estimate the financial losses within the petroleum industry and to measure the consequences on human health. The environmental loss is calculated by adopting the approach developed by Khan and Haddara (2003). A diagram will be proposed showing the steps that should be taken in order to support the maintenance team to decide whether to take an immediate action or postpone it to the next maintenance interval.

3.3 The Proposed Integrated Maintenance Framework

Framework is defined by the Oxford Dictionary as, "An essential supporting structure of a building, vehicle, or object". In general, a framework is a real or conceptual structure intended to serve as a support or guide for building something that further expands the structure into something useful. In computer systems, a framework is often a layered structure indicating what kind of programs can or should be built and how they would interrelate.

Some computer system frameworks also include actual programs, specify programming interfaces or offer programming tools for using the frameworks. A framework may be for a set of functions within a system and how they interrelate; the layers of an operating system; the layers of an application subsystem; how communication should be standardized at some level of a network; and so forth. A framework is generally more comprehensive than a protocol and more prescriptive than a structure.

An integrated framework is an analytical tool with several variations and contexts. It is used to make conceptual distinctions and organize ideas. Strong conceptual frameworks capture something real and do this in a way that is easy to remember and apply (Ravitch and Riggan, 2011).

Figure (3-3) demonstrates the high level diagram showing the main connections between the levels. It shows the each level and its main target and the links to another levels and activities.

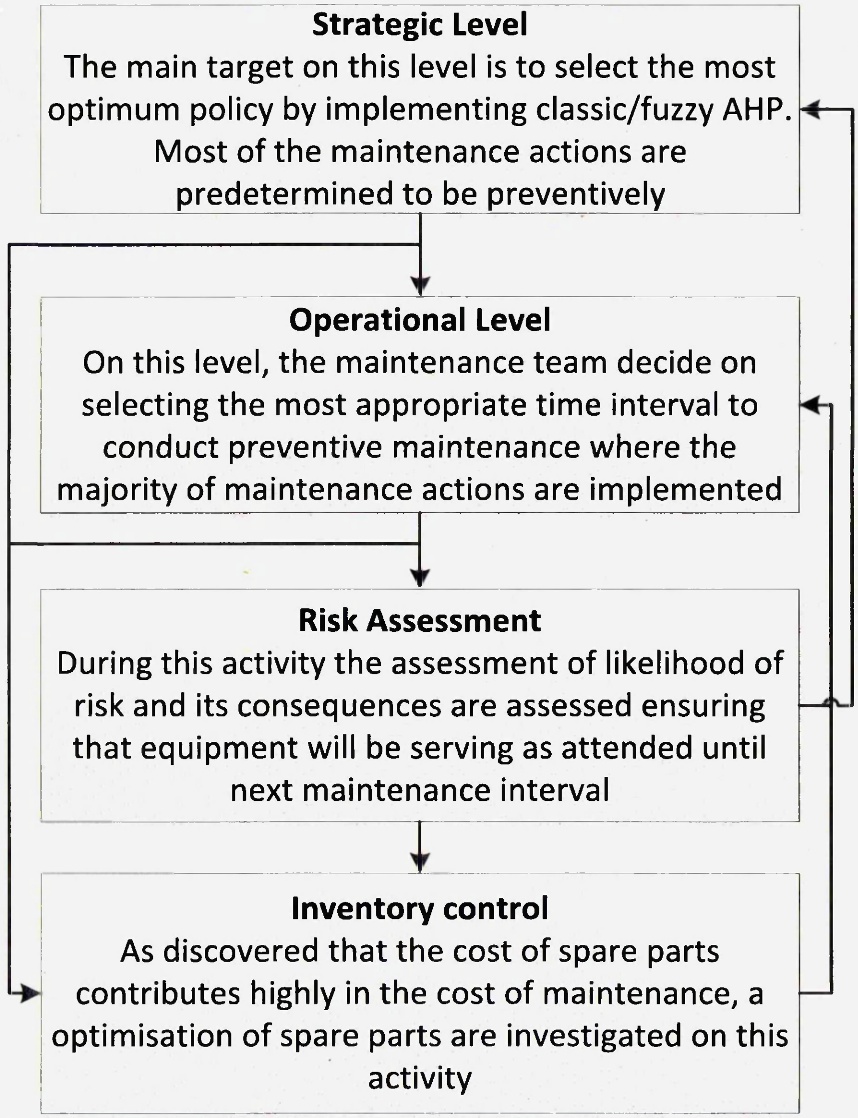


Figure 3-3: A Diagram showing the main connections Between Levels

3.3.1 Optimisation

The definition of optimisation in the Oxford online dictionary is, "the action of making the best or most effective use of a situation or resource". In mathematics, computer science and operations research, mathematical optimisation is the selection of a best element (with regard to some criteria) from some set of available alternatives. In this work, the optimisation of the entire maintenance activity is administered through the optimising the major activities of maintenance.

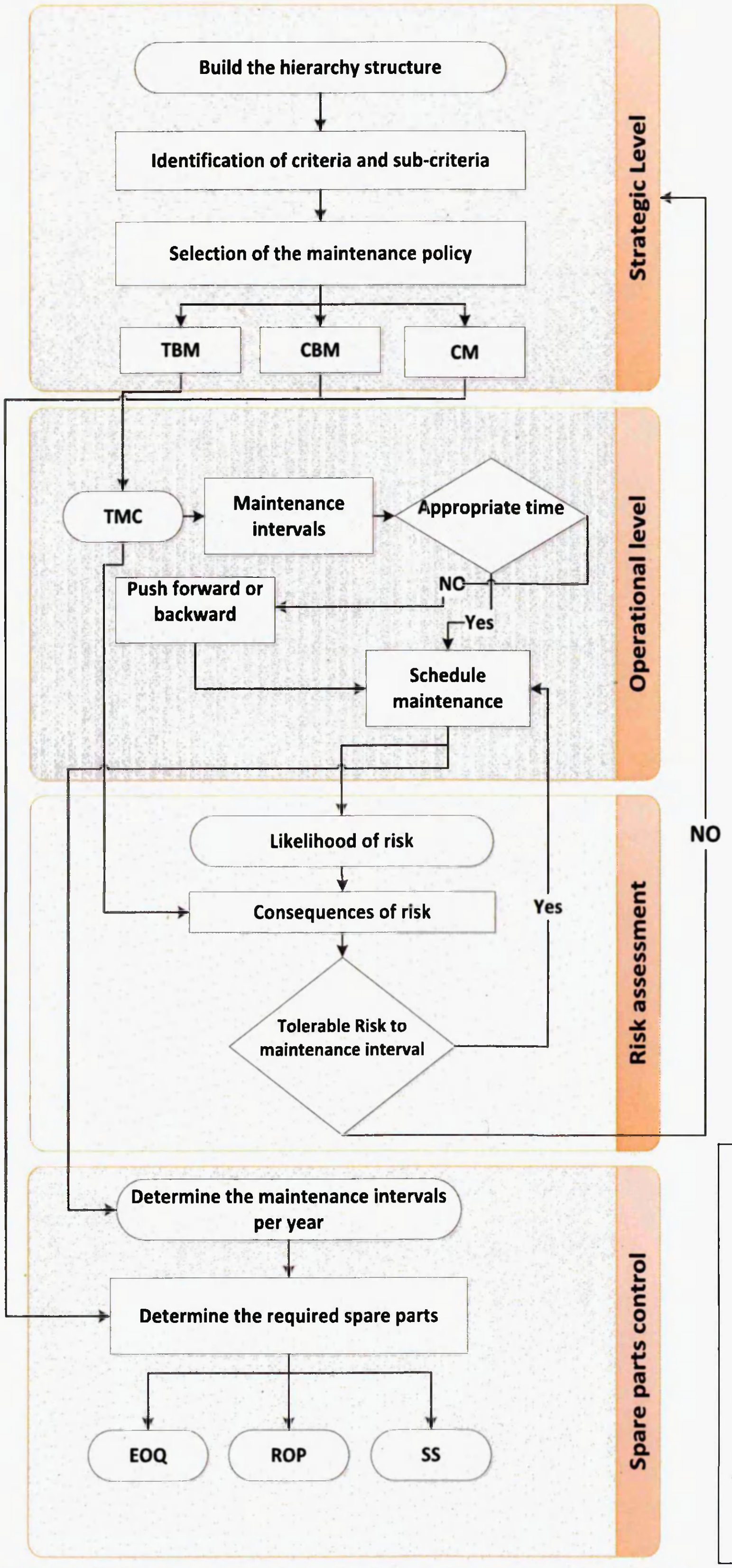
The optimisation of the selection of the most appropriate maintenance policy for equipment or its parts will be achieved by the comparison of the criteria, sub-criteria and available alternatives on the strategic level.

The scheduling of the maintenance activity will be conducted by mathematical programming. As the optimisation of a problem is to find the values of the variables that minimize or maximize the objective function, the proposed mathematical model will be seeking the optimum interval where the lowest cost can be achieved.

As the inventory of the spare parts is one of the main costs of the maintenance, an integrated approach will be proposed to seek the minimization of the cost of the spare parts inventory and it availability for the maintenance tasks.

The estimation of the risks within the petroleum fields is one of the main outputs of the maintenance and accordingly, a proposed mathematical model will be delivered to assess the likelihood of the risks and its estimated consequences. To achieve this target, a risk estimation model will comprehensively include or road map these proposed equations.

Figure (3-4) demonstrates the proposed integrated maintenance framework. The sequence of the proposed framework is to start with the strategic level and then move to the operation level. When the activities within these two levels are optimised, then the inventory spare parts and the risk assessment are optimised.



Keys:
CBM: Condition Based Maintenance
CM: Corrective maintenance
EOQ: Economic Order Quantity
ROP: Reordering Point
TBM: Time based Maintenance
TMC: Total Maintenance Cost
SS: Safety Stock

Figure 3-4: Proposed Integrated Maintenance Framework

3.3.2 Information

There are certain types of data and information that will be needed to validate the methodologies and ensure the practicality of the integrated framework. The type of data and information and its sources are listed below:

1. The input data for AHP which will be collected using a questionnaire, targeting academics and industrial staff involved within the petroleum industry, operations and maintenance personnel.
2. Preventive and corrective maintenance costs: The targeted case study (Petroleum Company) records and the advices of maintenance management team will be used to gather this information.
3. The history of the maintenance intervals and failure data: This will be obtained from the manual recommendation and maintenance log books.
4. Inventory of spare parts: This will be obtained from the inventory department records including the movement of spare parts including costs such as holding and ordering cost.

3.3.3 Integration

The maintenance strategic level, operation level, spare part management and risk assessment will be integrated as the recognised major activities within maintenance. To facilitate the thesis for the readers, each major activity will be discussed in individual chapters including the methodology which will be used to optimise the activity and its application.

3.3.4 Output

The output and integrations of certain activities will be validated by applying each proposed mathematical method and the results will be discussed at the end of each chapter. The selection of the most appropriate maintenance policy will be examined on the strategic level to ensure the suitability of the decision, while considering all related criteria by applying AHP/Fuzzy AHP method.

Optimisation of maintenance interval will be investigated by developing a mathematical programming method. A joint approach between maintenance intervals and spare parts control, to create cost optimisation approach, will be developed. Assessing the likelihood of risk through a mathematical model and evaluating the consequences of the risk will be carried out to validate the safety of the petroleum equipment.

3.4 Conclusion

In this chapter, an overall description of the methodologies that will be used to optimise each major activity associated with the maintenance function and the proposed integrated framework was presented. Four methodologies will be used for each activity.

Classical and fuzzy AHP will be applied in order to arrive at the optimum maintenance policy selection (Chapter Four) and a mathematical model will be developed to identify the optimum maintenance intervals as the majority of PM actions are based on time within the petroleum industry (Chapter Five). An integrated approach will be presented to optimise spare parts management (Chapter Six) and a set of equations will be either adapted or developed to optimise risk assessment within the petroleum industry (Chapter Seven).

The proposed integrated framework was introduced and the relevant terminologies were defined in this chapter to facilitate it for the readers to follow the forthcoming chapters and steps to optimise the major maintenance activities.

Chapter Four
Maintenance Strategic Level

This chapter covers the selection of maintenance policy (strategic level) within the petroleum industry. The creation of the model is proposed with its hierarchy structure and application of classic/ Fuzzy analytic hierarchy process is demonstrated. At the end of the chapter, a comparison between the various derivation methods and their response to the changes in consistency is illustrated.

4.1 Introduction

The selection of the most appropriate maintenance policy leads to the arrival at the optimisation of the entire operation of maintenance. Analytic hierarchy process (AHP) is considered as one of the most used methods of multi-criteria decision-making (MCDM) (Wang et al 2007). In oil and gas industry, diversity of machines align along the production line from upstream, midstream and to downstream. Therefore, different levels of reliability and availability of equipment is required. Moreover, their likelihood and consequences vary from machine to machine, which showcases the importance of analysing and questioning the selection of maintenance policy to enhance the overall system's productivity.

The selection of the maintenance policies is considered to be a complex matter and a trade-off between criteria is required to achieve the optimum maintenance selection. Decomposition of the structure of the hierarchy within AHP assists to identify the main criteria, sub-criteria and alternatives that impacts the selection of maintenance activities.

Classical AHP which refers to the handling of the matrix by the use of rigid numbers or the translation of linguistic preferences into rigid numbers is demonstrated within this chapter. Different methods of derivation of the priorities such as mean of the normalized values (MNV) and normalized geometric means (NGM) are applied on the collected data to investigate and compare the priorities. Eigenvector method (EVM) corresponding to the largest eigenvalue of the pairwise comparison matrix is used in this study and is considered to be one of the most popular approaches for deriving the weights associated with different entities (Lin and Lu, 2012). Fuzzy analytic hierarchy process is implemented and compared to the classical AHP methods at the end of this chapter. The rest of this chapter covers the problem modelling, "the hierarchy structure", weights derivation and aggregation using the classic AHP (different methods) and fuzzy AHP. Sensitivity analysis is performed to compare the sensitivity of each method and conclusion is drawn at the end of the chapter.

4.2 Hierarchy Structure for Optimum Maintenance Selection

The role of maintenance function has to be clearly defined to lead to the right selection of maintenance policies. The function of the machine, its required reliability, availability and consequences of failure has to be identified so as to avoid the wrong selection of maintenance method and causing less disturbance to the operations. In order to arrive at the selection of the most convenient maintenance policy within the oil and gas industry, identification of the criteria that impact the decision is vital of which the alternatives "time-based maintenance, condition-based maintenance and corrective maintenance" are selected. Maintenance policy selection is a hierarchy structure which includes the main target, criteria, sub-criteria and alternatives as presented figure (4-1). The proposed model was surveyed to arrive at the final version represented in Appendix (A).

Four main criteria have been identified (cost, availability, reliability and safety) and each of these criteria have identified factors (sub-criteria), which impact the main factor. Each main criterion and its sub-criteria are listed and defined in the following section:

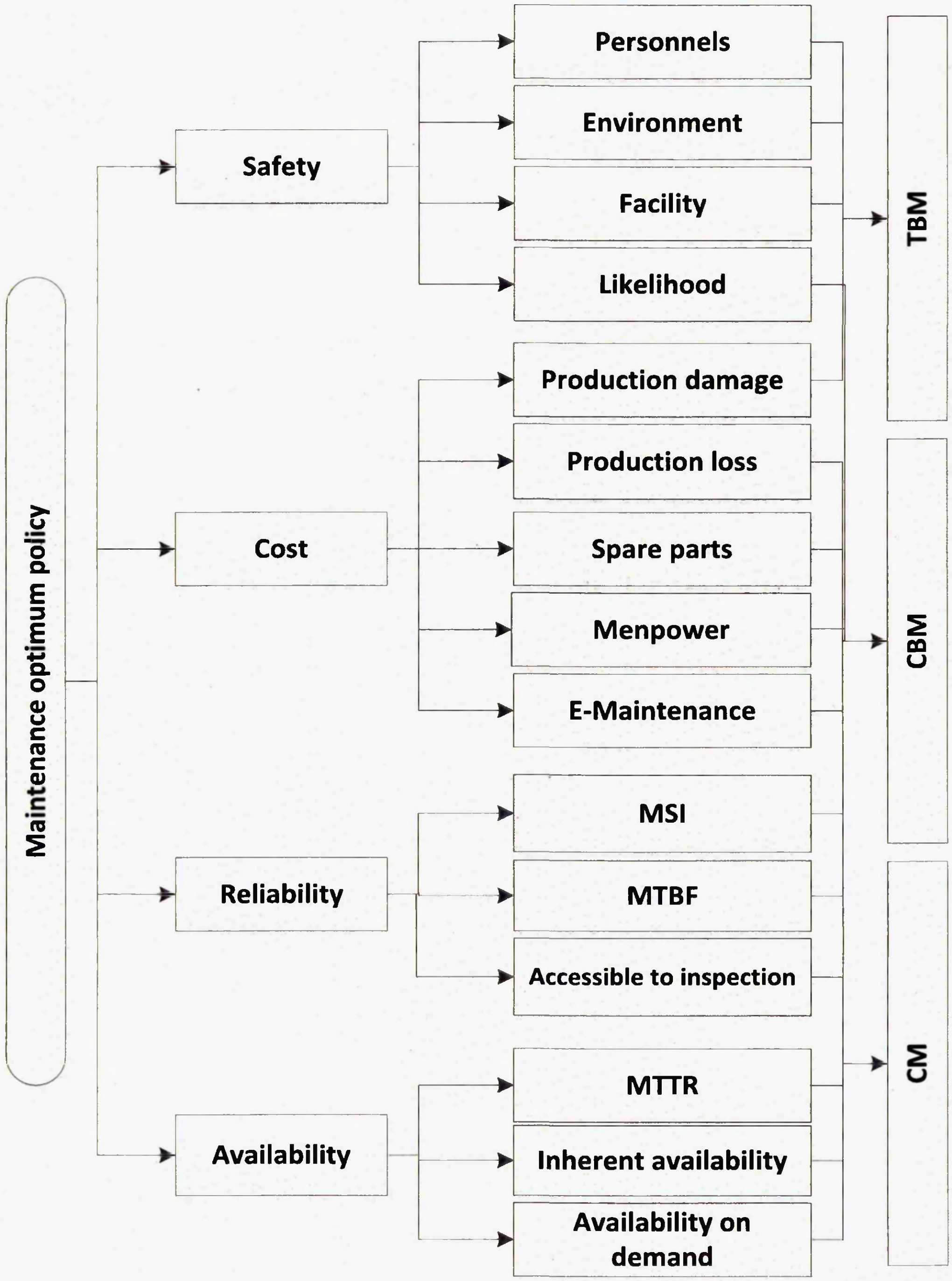


Figure 4-1: The Hierarchy Structure for the Maintenance Optimum Policy

4.2.1 Cost

Costs are incurred to keep equipment and its parts in a good condition. This main criterion influences the maintenance management decision on the policy that will be associated with the machines as each policy has consequentially different expenditure. Five major costs have been identified that contribute to the cost as main criterion:-

4.2.1.1 Manpower

The number of technicians needed in order to carry out each type of maintenance policy.

4.2.1.2 Spare parts

Spare parts are an essential sub criterion as the portion of their cost in terms of part cost and holding cost is one of the largest within the maintenance department.

4.2.1.3 Production Loss

This sub-criterion considers the loss of production as a consequence of failure and the stoppage while performing certain maintenance policy.

4.2.1.4 Production Damage

It indicates to the possibility of damaging the production due to the failure and damaged production is considered irreparable.

4.2.1.5 Computerized Maintenance: - "E-Maintenance"

Indicates the cost of the hardware "computers and sensors" and the cost of the software which is needed for analysing and measuring parameters data when using condition- based maintenance.

4.2.2 Availability

Availability is defined as a measure of the percentage of time the equipment is in an operable state. It can be computed as uptime divided by both uptime plus downtime (Anderson et all 2015). The criticality of availability of the asset is a main factor when assigning maintenance' policy on the strategic level. Three sub-criteria are identified that influence the availability of equipment.

4.2.2.1 Main Time to Repair (MTTR)

It is the time needed to repair or recover a system from the failure (Fiegler et al 2013). MTTR includes the time to diagnose the problem, the time to get the technicians and material required on-site and the total time needed to physically repair the equipment and hand it over to the operation department (Khalil et al, 2009).

4.2.2.2 Inherent Availability

Inherent availability considers the availability of the equipment and its importance and criticality to the system that might lead to putting down the system in case of a failure. The equipment is considered to be inherent to the system when, for instance, it has no stand-by equipment.

4.2.2.3 Availability on Demand

In this case, the availability of equipment is based on demand. For example, whether it has a spare system that can take over in case of maintenance or failure.

4.2.3 Reliability

Reliability is another main parameter to be taken into account when planning and managing assets' maintenance within the oil and gas industry. Reliability in general is a function of time, so pre-defined reliable system is a system that works as expected within a given time (Meeker and Luis, 2014). In the oil and gas industry, there are machines which require more level of reliability to increase the overall system reliability (Rausand and Vatn, 2004). Three sub-criteria have been identified and listed below.

4.2.3.1 Maintenance Significant Items (MSI)

It is a factor that considers the importance of equipment to the reliability of the system and if the machine would lead to shut down and disturb the process (Cheng et al 2008). Saranga (2002) selected the importance of equipment to the system using the risk priority number (RPN).

4.2.3.2 Accessible to Inspection

Accessibility to inspection indicates the accessibility of equipment and its parts that need to be inspected. The machine becomes reliable when data and information is available for the maintenance team to analyse. Reliability growth based inspection (RGBI) is one of the methods that are used for inspection in the oil and gas industry. This method uses power law analysis methodology to estimate further inspection (Calixto, 2012).

4.2.3.3 Mean Time between Failures (MTBF)

As the name suggests, it is the average time between failures. Márquez (2007) calculated the average mean time by dividing the time of incidents occurred by the number of incidents.

4.2.4. Safety

Safety level within the petroleum industry is considerably high, due to the possibility of risk of failure of some equipment and its catastrophic consequences (Mearns and Yule, 2009). In order to achieve the safety integrity level (SIL), where hazards can be tolerable, different tools such as hazard and operability analysis (HAZOP), fault tree analysis (FTA) and failure mode effect and criticality analysis (FMECA) can be used to identify the hazard (Andersen and Mostue, 2012). Four factors have been identified that impact safety as main criterion which are - likelihood of failure, personnel, facility and environment.

4.2.3.4 Likelihood of Failure

The likelihood of failure considers the possibility of equipment's failure. In other words, it answers the question "how likely is the occurrence of failure?" and in this context, risk can be defined both qualitatively and quantitatively (Khan and Haddara, 2003).

4.2.3.5 Personals

This sub-criterion considers the consequences of the failure on workers, where some machine can hazard environment in terms of failure.

4.2.3.6 Facility

This sub-criterion considers the impact of the failure on the machine itself or consequentially on other machines.

4.2.3.7 Environments

The failure of equipment might have adverse effects such as leakage of poisonous liquid or gas in the surrounding environment.

4.2.4 Alternatives

In this level, three possible alternative maintenance policies are considered as possible maintenance solution and they are listed as follows:-

4.2.4.1 Planed Corrective Maintenance (CM)

Corrective maintenance is the type of maintenance when the machine or part is run till failure. It is selected as planned under certain circumstances such as the failure of certain part would not cause any risk nor any financial losses.

4.2.4.2 Time Based Maintenance (TBM)

TBM is planned preventive maintenance and performed periodically "calendar time, operating time or age" to reduce frequent and sudden failure. Within the petroleum industry, this maintenance policy would be implemented for majority of equipment for periods which are called overhaul or turnaround maintenance time.

4.2.4.3 Condition Based Maintenance (CBM)

CBM is the type of preventive maintenance policy which is performed depending on the condition of the machine. Thus the machine is monitored till it shows signs of degradation and then maintenance is called to take place. Techniques such as vibration monitoring, lubrication analysis and ultrasonic testing are used to monitor the health of the machine.

4.3 Collection of Judgment Data

Collection of data was carried out in order to validate the proposed maintenance policy selection framework. The collection of the data was concerning the pair wise comparison, where the participants would provide their own judgment to each criterion in comparison to others within the same level. The questionnaire was developed (Appendix B), covering each of the levels of the hierarchy structure and the criteria within each level. Fifty participants from academic and industrial background took part in the research and contributed to complete the questionnaire.

4.3.1 The Judgement Scales

To evaluate the criteria in each level in comparison to other criteria included in the next hierarchy level, scoring is made with the utilization of standard scale provided by the AHP software. Table (4-1) is applied which is adopted from Saaty (Saaty 1994; Malczewski 1999; Saaty 2008; Akıncı et al 2013).

Table 4-1: Scale of Relative Importance

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favour one activity over another
5	Essential or strong importance	Experience and judgment strongly favour one activity over another
7	Demonstrated importance	An activity is strongly favoured and its dominance demonstrated in practice
9	Absolute importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

4.3.2 The Generation of the Comparison Matrix

In this section, the matrices are built in each level with respect to the higher level. The inserted values are the sum of the geometric mean which has been collected through a questionnaire. The first matrix is to compare the main criteria "reliability, availability, safety and cost" with respect to the main goal as shown in table (4-2).

Table 4-2: Comparison Matrix of Main Criteria

main criteria	Cost	Availability	Reliability	Safety
Cost	1	1/7	1/5	1/3
Availability	7	1	1	3
Reliability	5	1	1	5
Safety	3	1/3	1/5	1

4.3.3 Consistency

Once the weights have been allocated and recorded for each criterion, a consistency check has to be performed. Saaty (1980) suggested the consistency index (*CI*) to measure the degree of consistency using the following equation:-

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad 4\text{-}1$$

Where: -

λ_{max} Maximal eigenvalue

n Size of the matrix

Then the consistency ratio (CR) is generated by the comparison of value of consistency index *(CI)* and random indices *(RI)*:-

$$CR = \frac{CI}{RI} \qquad 4\text{-}2$$

CR ≤ 0.1 can be taken as sufficiently consistent Saaty (1990). Saaty (1977) calculated the random indices (RI) shown in table (4-3). Other researchers have run simulations with similar numbers of matrices such as Lane and Verdini (1989); Forman (1990); Tummala and Wan (1994); Alonso, Lamata (2006) and Ishizaka and Labib (2009) and their random indices are different but close to Saaty's RI. In this work, the consistency is investigated by the use of Expert Choice.

Table 4-3: Random Indices (Ishizaka and Labib 2009)

n	3	4	5	6	7	8	9	10
RI	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

4.4 Pairwise Matrix Evaluation

In this work, Expert Choice software was adopted in order to assess the priorities between the criteria, sub-criteria and alternatives. However, different methods (mean of the normalised values (MNV), normalised geometric Mean (NGM) and eigenvector mean (EVM)) were used to derive the priorities within the comparison matrixes to satisfy and compare it with the outcome of the software and later on with the Fuzzy AHP.

4.4.1 Applications of Mean Normalised Value

To demonstrate the process of the MNV method, the matrix of the main criteria (Table 4-2) is demonstrated as:-

Step (1): Equation (4-3) is applied to calculate the sum of the columns which results into :-(cost =16, availability =2.48, reliability =2.4 and safety = 9.33).

$$\frac{p_1}{p_j} + \frac{p_2}{p_j} + \frac{p_3}{p_j} \dots\dots \frac{p_4}{p_j} + \frac{p_n}{p_j} = \frac{\sum_{i=1}^{n} Pi}{Pj} \qquad 4\text{-}3$$

Where a_{ij} is the comparison between $i$and j and Pi is the priority of i.

Step (2): Equation (4-4) is applied to normalize the columns by dividing each column's values by its sum and the results are listed in table (4-4).

Table 4-4: The Normalized Value (MNV)

Main criteria	Cost	Availability	Reliability	Safety
Cost	0.06	0.06	0.08	0.04
Availability	0.44	0.40	0.42	0.32
Reliability	0.31	0.40	0.42	0.54
Safety	0.19	0.13	0.08	0.11

$$\frac{\frac{p_i}{p_j}}{\frac{\sum_{i=1}^{n} p_i}{p_j}} = \frac{P_i}{P_j} \times \frac{P_j}{\sum_{i=1}^{n} P_i} = \frac{P_i}{\sum_{i=1}^{n} P_i} \qquad 4\text{-}4$$

Step (3): equation (4-5) is applied to calculate the mean value for each row which is the weight of the criterion.

The results of applying MNV method shows that reliability of the equipment comes as the most preferred criterion (reliability = 0.42) followed by availability of the equipment (0.39), safety (0.13) and cost with the least ranking (0.06) as shown in figure (4-2).

$$\left(\frac{P_i}{\sum_{i=1}^{n} P_i} + \cdots + \frac{P_i}{\sum_{i=1}^{n} P_i}\right) \times \frac{1}{n} = \frac{n \times p_i}{\sum_{i=1}^{n} P_i} \times \frac{1}{n} = \frac{P_i}{\sum_{i=1}^{n} P_i} \qquad 4\text{-}5$$

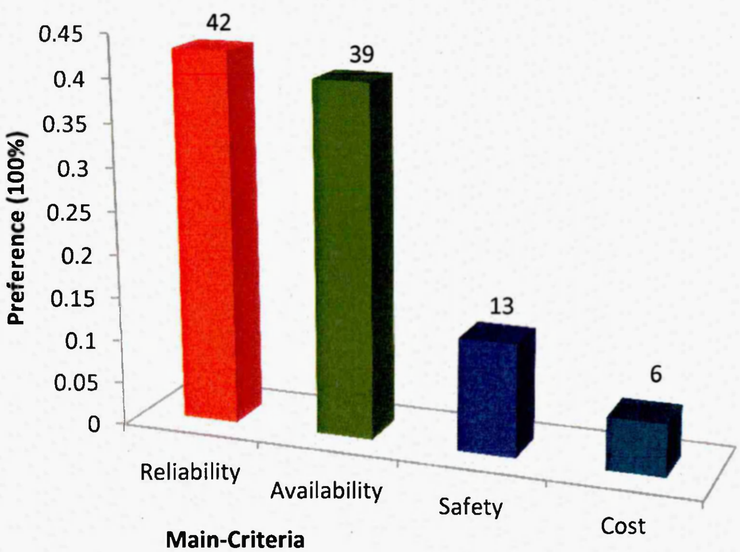


Figure 4-2: Priority Preference of Main Criteria Using MNV

Table (4-5) demonstrates the alternative's preference with respect to (cost). After finding the priorities of sub-criteria of the cost, the preference of alternatives is computed for each of them. The preference of the alternatives of sub criterion is then multiplied by the weight of its sub criterion. Each of the alternatives (TBM, CBM and CM) resulted weight are then added together to calculate the weight of each of them with respect to cost.

Table 4-5: Weight of Priorities with Respect to Cost (NMV)

Main Criteria %	Sub-Criteria %	Local Alternatives Weights	Alternative Weight with Respect to Cost %
cost 0.06	Pro-loss 0.494	TBM 0.45 CBM 0.45 CM 0.09	TBM=0.5255 CBM=0.3855 CM=0.089
	Pro-damage 0.222	TBM 0.45 CBM 0.45 CM 0.09	
	Spare-parts 0.16	TBM 0.79 CBM 0.12 CM 0.09	
	Men-power 0.084	TBM 0.64 CBM 0.28 CM 0.08	
	E-maintenance 0.046	TBM 0.43 CBM 0.43 CM 0.08	

Figure (4-3) presents the alternative's preference with respect to cost. Therefore in the case of cost becoming the absolute priority among other criteria TBM would be the most preferred maintenance policy.

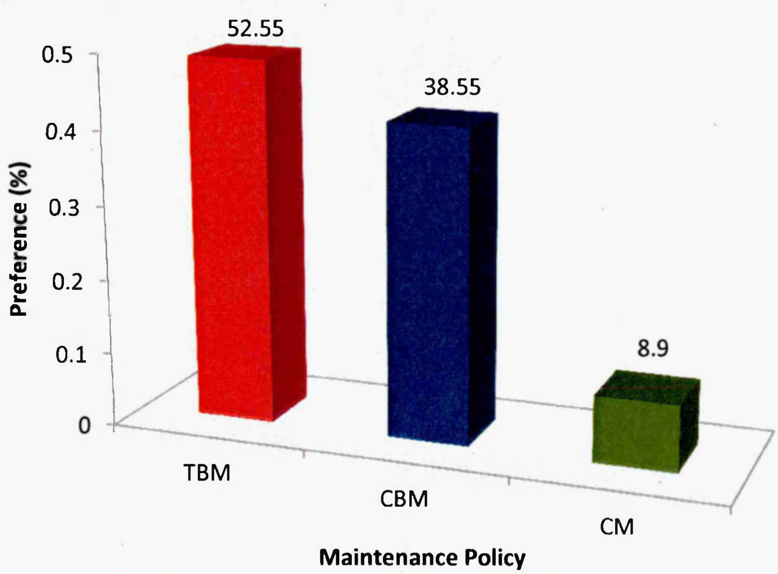


Figure 4-3: Alternative Priorities with Respect to Cost

Table (4-6) sums the weight of the local and global priorities of the criteria, sub-criteria and alternatives resulted by applying the same steps above of NMV.

Table 4-6: Local, Global Priorities and Alternatives Weight (NMV)

Main criteria %	Sub-criteria %	Local alternatives weight with respect to sub-criteria %	Local alternatives with respect to main-criteria %	Alternatives global weight %
Cost 0.06	Pro-loss 0.494	TBM 0.45 CBM 0.45 CM 0.09	TBM 0.0133 CBM 0.0133 CM 0.00267	TBM= 0.47 CBM= 0.439 CM=0.089
	Pro-damage 0.222	TBM 0.45 CBM 0.45 CM 0.09	TBM 0.00599 CBM 0.00599 CM 0.0012	
	Spare-parts 0.16	TBM 0.79 CBM 0.12 CM 0.09	TBM 0.00758 CBM 0.00115 CM 0.00086	
	Man-power 0.084	TBM 0.64 CBM 0.28 CM 0.08	TBM 0.00323 CBM 0.00141 CM 0.0004	
	E-maintenance 0.046	TBM 0.43 CBM 0.43 CM 0.08	TBM 0.00119 CBM 0.00119 CM 0.00022	
Reliability 0.42	MSI 0.71	TBM 0.45 CBM 0.45 CM 0.09	TBM 0.13419 CBM 0.13419 CM 0.02684	
	ATI 0.14	TBM 0.45 CBM 0.45 CM 0.09	TBM 0.02646 CBM 0.02646 CM 0.00529	
	MTBF 0.14	TBM 0.45 CBM 0.45 CM 0.09	TBM 0.02646 CBM 0.02646 CM 0.00529	
Availability 0.39	Inherent availability 0.26	TBM 0.45 CBM 0.45 CM 0.09	TBM 0.04563 CBM 0.04563 CM 0.00913	
	MTTR 0.11	TBM 0.45 CBM 0.45 CM 0.09	TBM 0.01931 CBM 0.01931 CM 0.00386	
	Availability on demand 0.64	TBM 0.49 CBM 0.43 CM 0.08	TBM 0.1223 CBM 0.1073 CM 0.01997	
Safety 0.13	Risk likelihood 0.60	TBM 0.45 CBM 0.45 CM 0.09	TBM 0.0351 CBM 0.0351 CM 0.00702	
	Environment 0.14	TBM 0.45 CBM 0.45 CM 0.09	TBM 0.00819 CBM 0.00819 CM 0.00164	
	Facility 0.11	TBM 0.45 CBM 0.45 CM 0.09	TBM 0.00644 CBM 0.00644 CM 0.00131	
	Personnel 0.16	TBM 0.63 CBM 0.26 CM 0.11	TBM 0.0131 CBM 0.00541 CM 0.00229	

Equation (4-6) demonstrates the steps of calculating the global alternatives weight. Each weight of local alternatives with respect to sub-criteria is multiplied by the weight the sub-criteria and the weight of main criteria which results into small alternatives weights which are then summed up.

$$Global\ alternative\ weight\ G_{AW} = \sum W_{MC} \times W_{SC} \times A_{WSC} \qquad 4\text{-}6$$

Where:-

W_{MC} Weight of main criteria.

W_{SC} Weight of sub criteria.

A_{WSC} Alternative's weight of sub criteria.

Figure (4-4) illustrates the prioritisation of the alternatives (maintenance policies) with respect to the main goal by the use of MNV. TBM is the most preferred alternative with global weight (47%), followed by the CBM (43.9%) and CM with the least weight (8.9%).

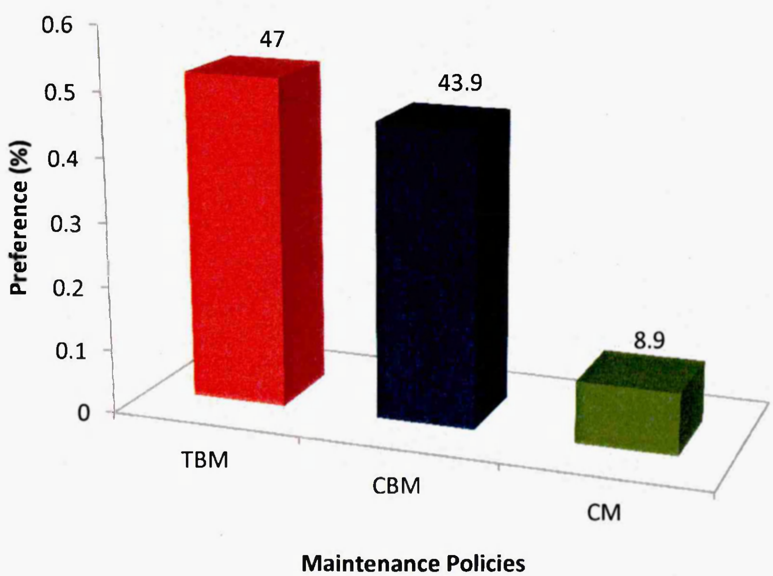


Figure 4-4: Priorities of Alternatives Using MNV Method

4.4.2 Application of Normalised Geometric Mean (NGM)

The normalised geometric mean is an alternative measure of the priorities and is formed by taking the root of the product matrix of row elements divided by the column sum of row geometric means. Equation (4-7) is applied to calculate the geometric mean for each row p. The matrix of main criteria is applied and results shown in table (4-7).

$$p = \sqrt[n]{a.b.c \dots .n} \qquad 4\text{-}7$$

Where:- $a,.b.,c$ and n are the comparison values for each rows

Table 4-7: Normalised Geometric mean of The Main Criteria

Criteria	Cost	Availability	Reliability	Safety	Geometric mean
Cost	1	1/7	1/5	1/3	0.31
Availability	7	1	1	3	2.14
Reliability	5	1	1	5	2.14
Safety	3	1/3	1/5	1	0.67

The second step is to summarize the results of the criteria of the rows as followed: - (0.31+2.14+2.24+0.67= 5.36).Finally, normalizing the results to obtain the priorities for the matrix of the main - criteria and the priorities are computed as followed (cost 0.06, availability 0.40, reliability 0.42, and safety 0.12). The same abovementioned steps are followed for the rest of the matrix in order to calculate the global priorities of the alternatives.

Table (4-8) demonstrates the results of applying NGM and shows the weight of the main criteria, sub criteria and global alternative. The local alternative weights are provided with respect to the sub-criteria. The advantage of having the local priorities for the maintenance is to provide them with a predefined solution, for instance, if the circumstances are changed.

Table 4-8: Local, Global priorities and Alternatives Weight (NGM)

Main criteria %	Sub-criteria %	Local alternatives weight with respect to sub-criteria %	Alternative global weight %
cost 0.06	Pro-loss 0.50	TBM 0.45 CBM 0.45 CM 0.09	TBM=0.47045 CBM=0.44167 CM=0.08857
	Pro-damage 0.22	TBM 0.45 CBM 0.45 CM 0.09	
	Spare-parts 0.16	TBM 0.81 CBM 0.10 CM 0.09	
	Men-power 0.08	TBM 0.65 CBM 0.28 CM 0.07	
	E-maintenance 0.05	TBM 0.43 CBM 0.43 CM 0.14	
Reliability 0.44	MSI 0.71	TBM 0.45 CBM 0.45 CM 0.09	
	ATI 0.14	TBM 0.45 CBM 0.45 CM 0.09	
	MTBF 0.14	TBM 0.45 CBM 0.45 CM 0.09	
Availability 0.39	Inherent availability 0.26	TBM 0.45 CBM 0.45 CM 0.09	
	MTTR 0.10	TBM 0.45 CBM 0.45 CM 0.09	
	Availability on demand 0.64	TBM 0.49 CBM 0.44 CM 0.08	
Safety 0.12	Risk likelihood 0.60	TBM 0.45 CBM 0.45 CM 0.09	
	Environment 0.14	TBM 0.45 CBM 0.45 CM 0.09	
	Facility 0.10	TBM 0.45 CBM 0.45 CM 0.09	
	Personnel 0.16	TBM 0.64 CBM 0.26 CM 0.11	

Figure (4-5) presents the global alternative (maintenance policies) priority with respect to main goal (maintenance selection policy) using NGM (TBM 0.47045, CBM 0.44167 and CM 0.08857).

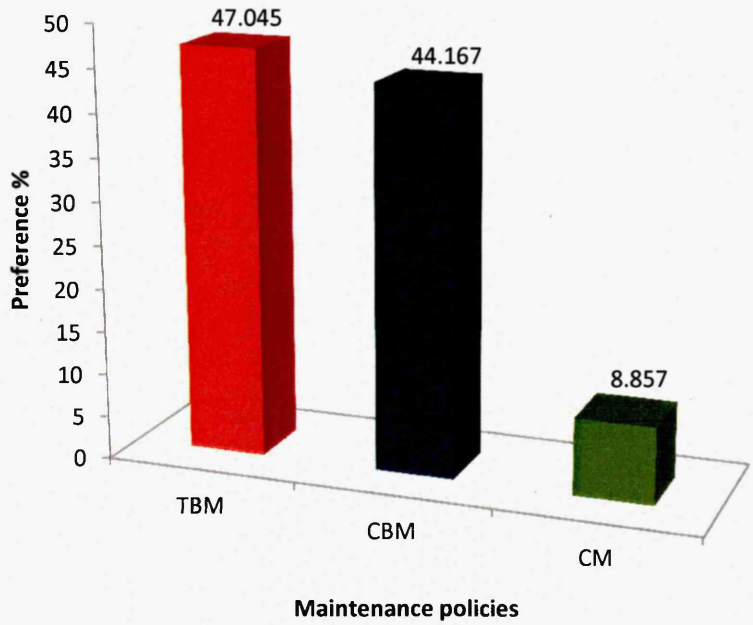


Figure 4-5: Alternative Preference With Respect to Main Goal (NGM)

4.4.3 Applications of Eigenvector Method (EVM)

This is the original Saaty's approach to derive the priorities from the AHP method. In this work, Expert Choice Software is used which follows the EVM process to generate the weights, priorities and alternatives for the criteria. The following section will demonstrate the steps that were taken to arrive at the prioritization of alternatives using the EVM method.

4.4.3.1 Problem Modelling

In this step, the problem is created on the software, hierarchically from the goal (maintenance optimum strategy) to the main criteria, sub-criteria and then to the alternatives (TBM, CBM and CM).

Figure (4-6) shows the hierarchical view of the problem modelling. Expert Choice provides familiar and a comprehensible interface for users to create the hierarchy. In order to provide comprehensive view of the structure, the alternatives are not expanded for all the sub-criteria, but instead they are expanded for one sub-criterion (maintenance significant Items).

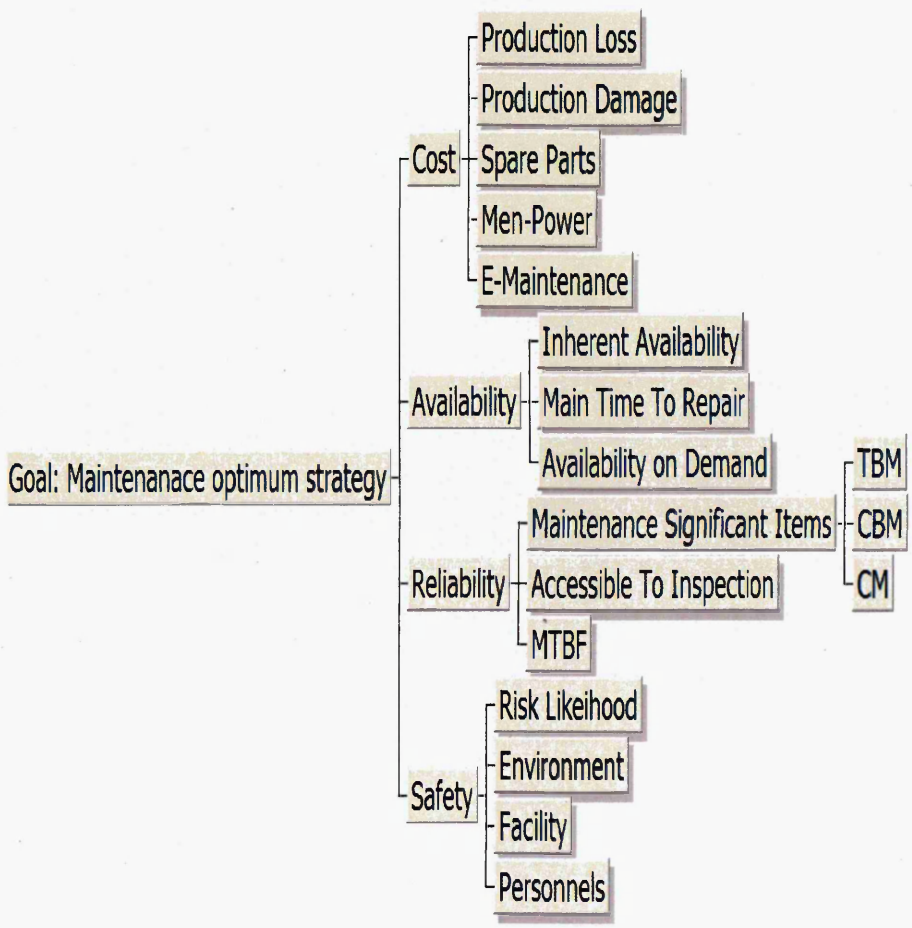


Figure 4-6: A Hierarchal View of the Entire Structure

4.4.3.2 Pairwise Comparisons

At each node of the hierarchy, a matrix is entered for the pairwise comparisons through the use of ratio scale (Kainulainen et al. 2009).The data can be entered by pairwise numerical comparisons (figure 4-7).

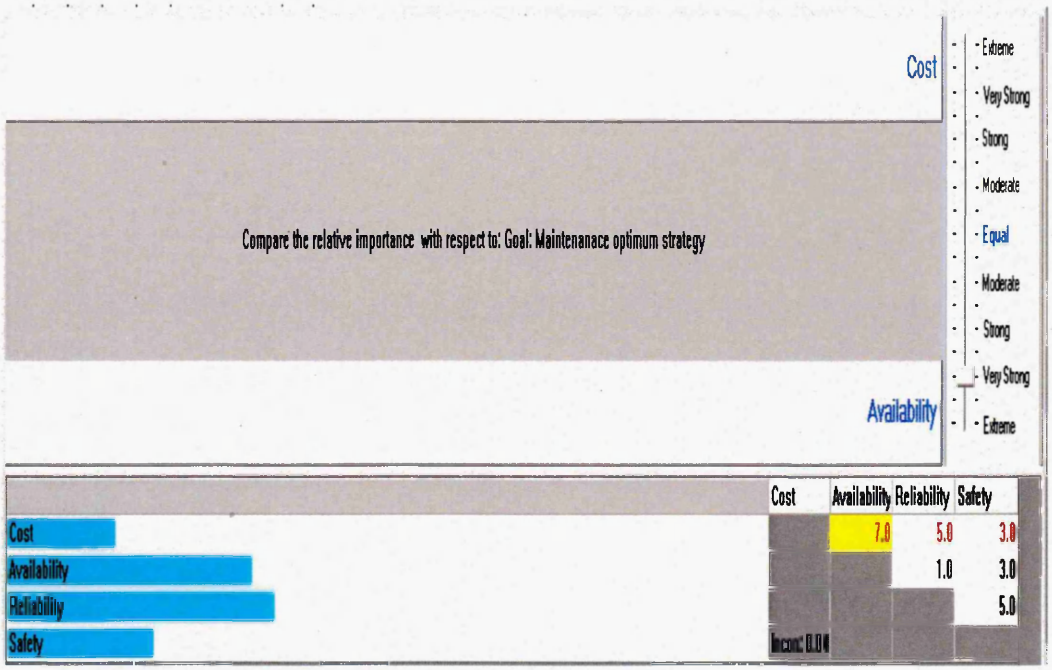


Figure 4-7: Pairwise Numerical Comparisons

4.4.3.3 Consistency

Once the comparison judgment is entered for each matrix, it is possible to check the consistency. The possibility of assessing the highest criteria that contributes to consistency is provided by Expert Choice (figure 4-8).

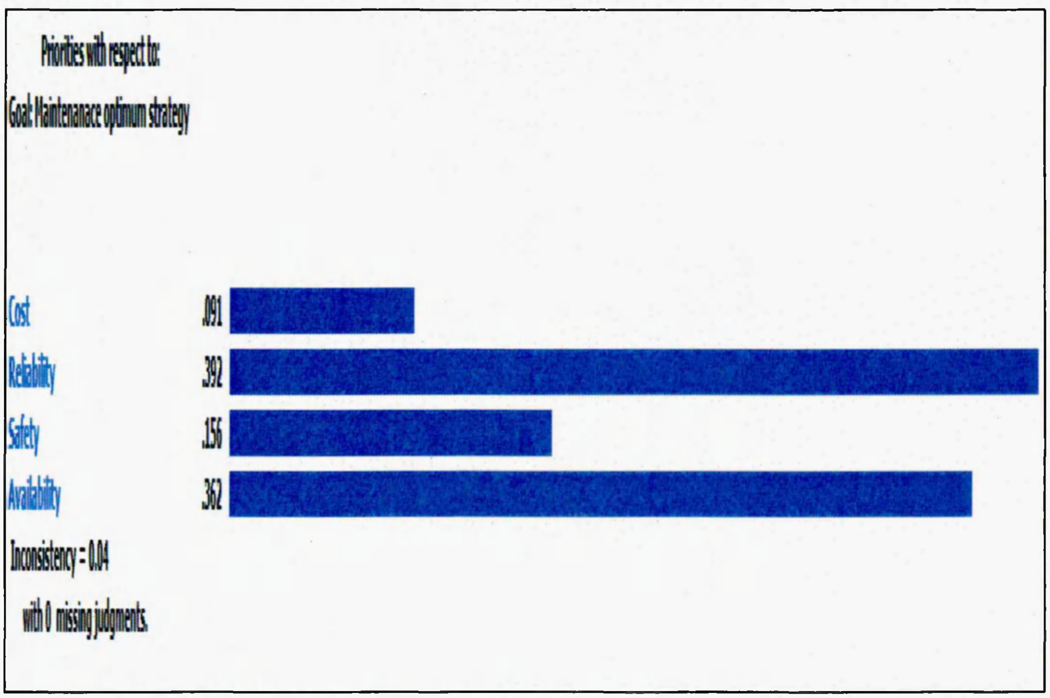


Figure 4-8: Main Criteria Prioritization and Inconsistency Measurement

Figure (4-9) displays the family tree generated by the use of Expert Choice that shows the weights of each criteria, sub-criteria and alternatives. The global alternatives are provided as well and the possibility of generating the local alternative priority is provided by the Expert Choice.

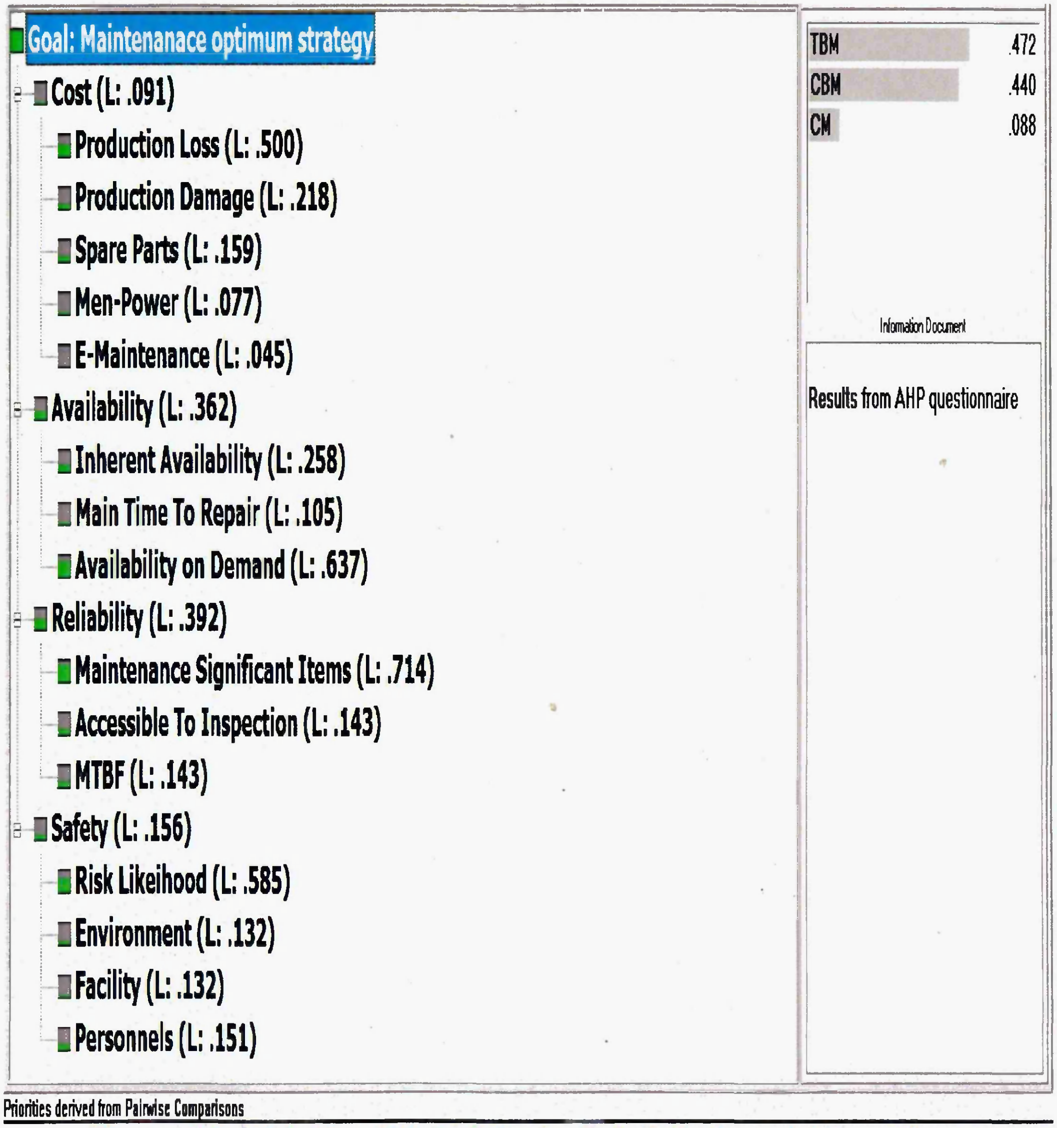


Figure 4-9: Weights of Main Criteria, Sub Criteria and Alternatives

Table (4-9) demonstrates the results of the weights for the main criteria, sub criteria and local and global alternatives. Local alternatives for each node sub criteria are displayed and the global alternatives with respect to the main goal (maintenance optimum strategy) are demonstrated.

Table 4-9: Local, Global priorities and Alternatives Weight (EVM)

Main criteria %	Sub-criteria %	Local alternatives weight with respect to sub-criteria %	Alternative global weight %
cost 0.091	Pro-loss 0.50	TBM 0.455 CBM 0.455 CM 0.091	TBM=0.472 CBM=0.440 CM=0.088
	Pro-damage 0.218	TBM 0.455 CBM 0.455 CM 0.091	
	Spare-parts 0.159	TBM 0.731 CBM 0.188 CM 0.081	
	Man-power 0.077	TBM 0.649 CBM 0.279 CM 0.072	
	E-maintenance 0.045	TBM 0.429 CBM 0.429 CM 0.143	
Reliability 0.392	MSI 0.714	TBM 0.455 CBM 0.455 CM 0.091	
	ATI 0.143	TBM 0.455 CBM 0.455 CM 0.091	
	MTBF 0.143	TBM 0.455 CBM 0.455 CM 0.091	
Availability 0.362	Inherent availability 0.258	TBM 0.455 CBM 0.455 CM 0.091	
	MTTR 0.105	TBM 0.455 CBM 0.455 CM 0.091	
	Availability on demand 0.637	TBM 0.487 CBM 0.435 CM 0.078	
Safety 0.156	Risk likelihood 0.585	TBM 0.455 CBM 0.455 CM 0.091	
	Environment 0.132	TBM 0.455 CBM 0.455 CM 0.091	
	Facility 0.132	TBM 0.455 CBM 0.455 CM 0.091	
	Personnel 0.151	TBM 0.631 CBM 0.258 CM 0.101	

Figure (4-10) demonstrates the global alternatives priority resulting from applying EVM derivation method. The priority of the maintenance policies goes first to TBM with 47.2% followed by CBM with 44% and CM with 8.8%.

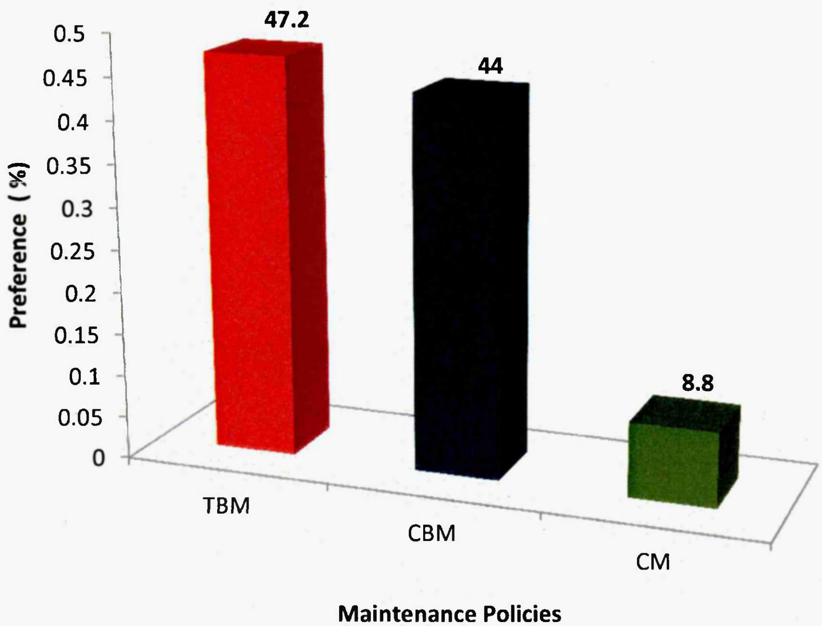


Figure 4-10: Alternative Preference with Respect to Main Goal Using (EVM)

4.4.4 Sensitivity analysis

The last step of the decision process within the Expert Choice is the sensitivity analysis, where the input data are slightly modified in order to observe the impact on the alternatives. If the ranking does not change, the results are considered to be robust. Expert Choice allows different sensitivity analyses, where the main difference is the various graphical representations as shown in figure (4-11).

The main criteria preferences ware modified slightly at the beginning to ensure that the selection of the alternatives preference was rigid or otherwise the prioritization of alternatives would be focused on understanding the consequences of the changes within the alternatives.

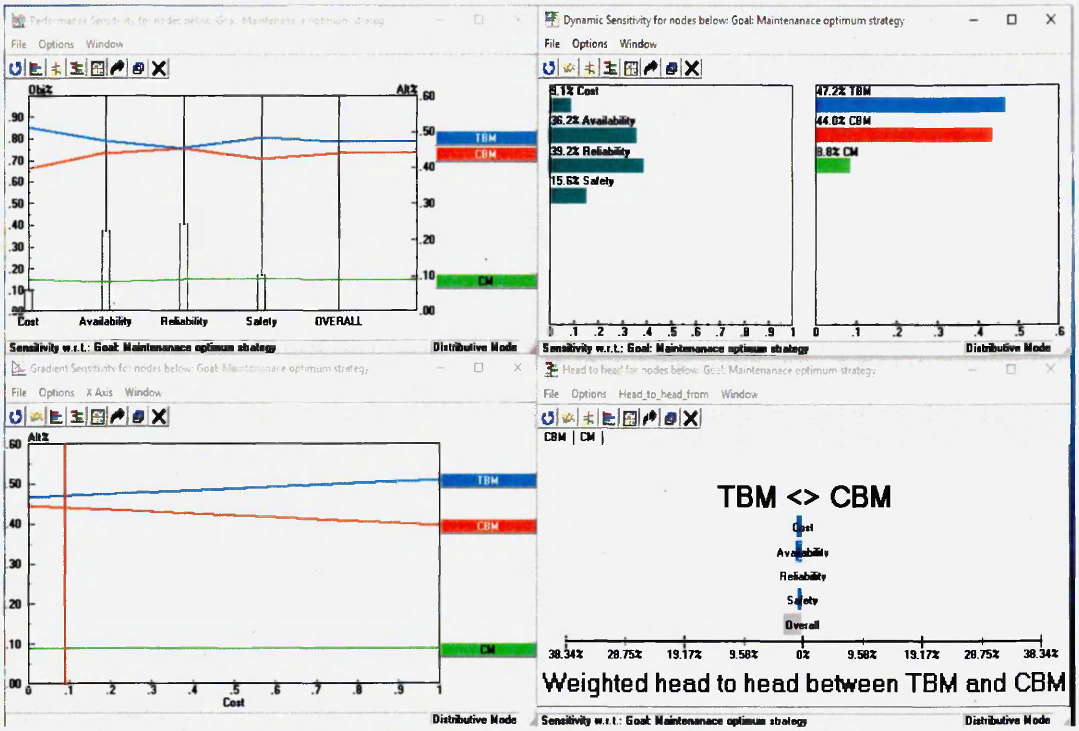


Figure 4-11: Different Sensitivity Analysis Graphs

Figure (4-12) demonstrates the dynamic sensitivity analysis which is one of the available methods of sensitive analysis. In this case, it shows that if the reliability of the equipment was the only important criterion than the CBM and TBM becomes equally important.

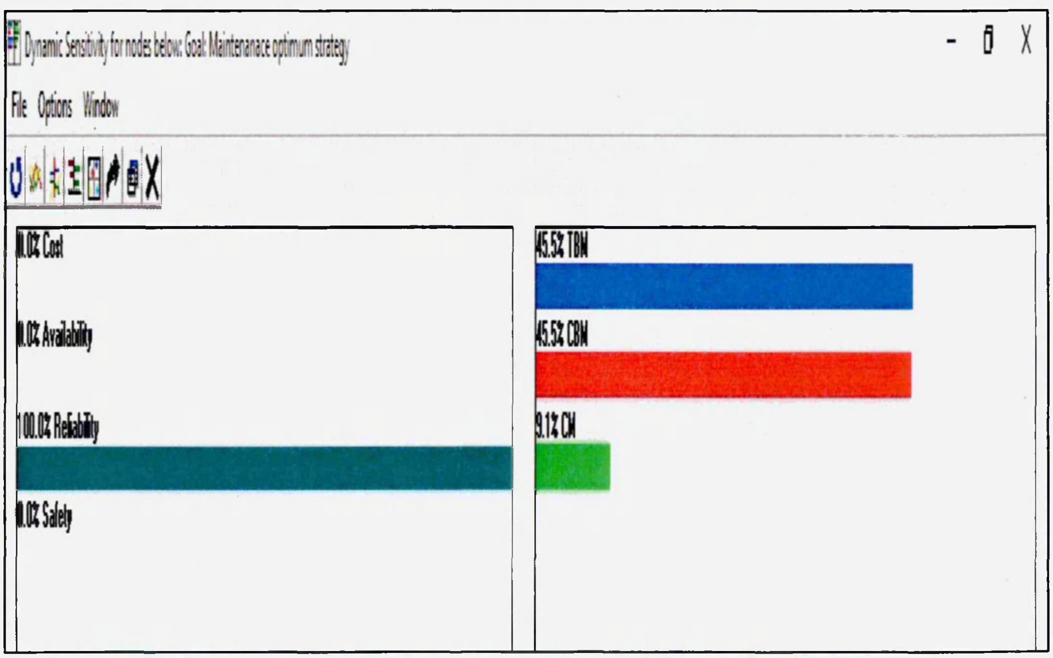


Figure 4-12: Dynamic Sensitivity for the Main Criteria

4.5 Fuzzy Analytic Hierarchy Process (FAHP)

Figure (4-13) presents the membership function using triangular fuzzy number (TFN). The method computes eigenvectors until the composite final vector is obtained. The final vector of weights (global weight) shows the relative importance of each alternative towards the main goal (Sharma and Yu 2014).

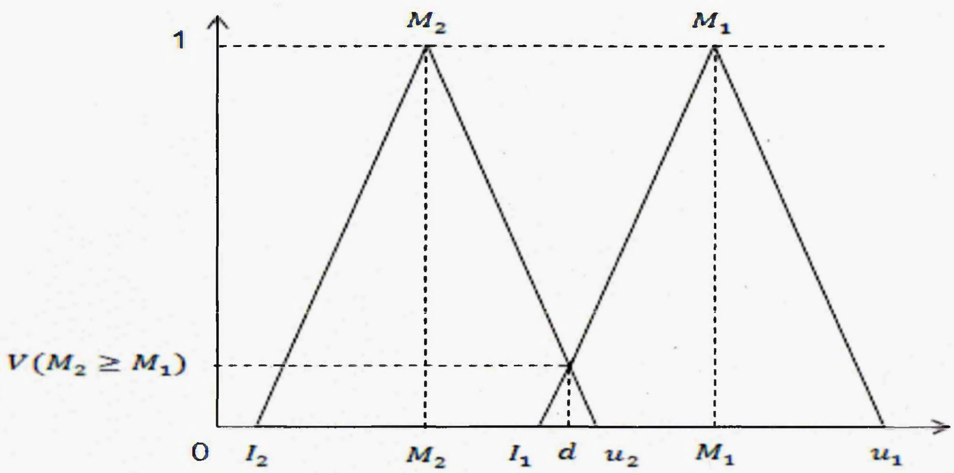


Figure 4-13: The Intersection between TFNs (Sharma and Yu 2014)

The membership function of TFNs can be described by the following equation (4-8):-

$$\mu_M(x) = \begin{cases} \frac{x}{m-l} - \frac{l}{m-l}, & x \in [l,m] \\ \frac{x}{m-u} - \frac{u}{m-u}, & x \in [m,u] \\ 0, & otherwise \end{cases} \qquad 4\text{-}8$$

The TFN membership is often represented as(l, m, u). Where l, is the lower bound value, m is the middle bound and u is the upper bound value. Fuzziness can always be given by its corresponding left and right representation as in equation (4-9) (Prakash, 2003).

$$\tilde{M} = M^{l(y)} = M^{l(y)} = [l + (m-l)y, u + (m-u)y], y \in [0,1] \qquad 4\text{-}9$$

Where $l(y)$ and $r(y)$ represents left side and right side of fuzzy numbers.

TFNs have various operations and only important ones are used in this study.

Two fuzzy numbers $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$ have been given as follows (Saad et al 2016):-

$$(l_1, m_1, u_1) \oplus (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \quad \text{4-10}$$

$$(l_1, m_1, u_1) \ominus (l_2, m_2, u_2) = (l_1 - l_2, m_1 - m_2, u_1 - u_2) \quad \text{4-11}$$

$$(l_1, m_1, u_1) \otimes (l_2, m_2, u_2) = (l_1 * l_2, m_1 * m_2, u_1 * u_2) \quad \text{4-12}$$

$$(l_1, m_1, u_1) \oslash (l_2, m_2, u_2) = (l_1/l_2, m_1/m_2, u_1/u_2) \quad \text{4-13}$$

4.5.1 Preference Scale

Figure (4-14) shows the triangular fuzzy membership function. The linguistic scale for importance is the various fuzzy sets.

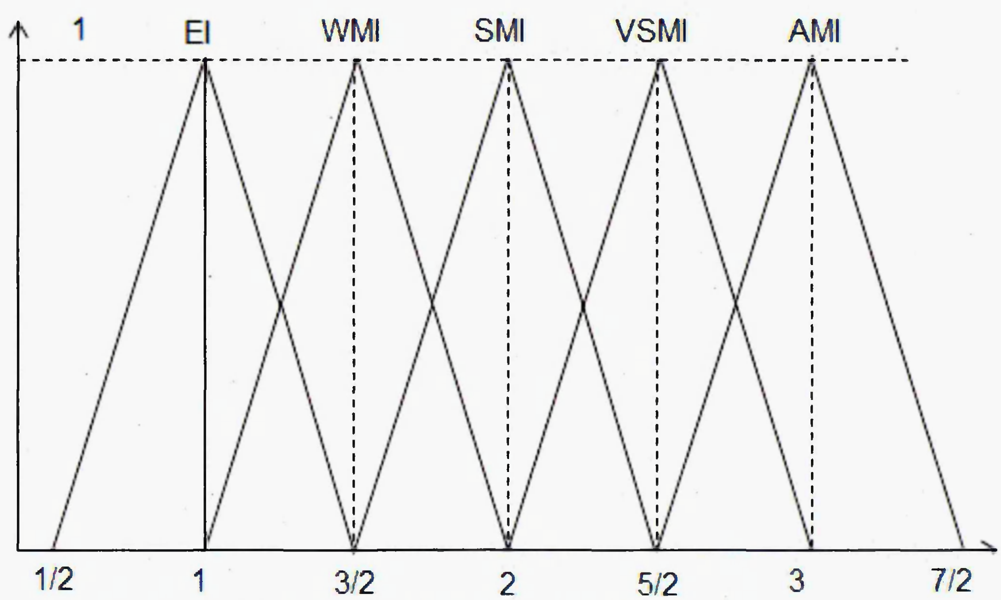


Figure 4-14: Triangular Fuzzy membership (Sarfaraz et al 2012)

Different scales are proposed for the conversion scale. Table (4-10) fuzzy AHP is a range of values in order to deal with uncertainties for decision makers (Sarfaraz et al 2012).

Table 4-10: Triangular Fuzzy Conversion Scale (Sarfaraz et al 2012)

Linguistic scale	Importance Intensity	Triangular Fuzzy scale	Importance Intensity	Reciprocal Triangular Fuzzy Scale
Equally important (EI)	1	(1/2,1,3/2)	1/1	(1/2,1,3/2)
Weakly more important (WMI)	3	(1,3/2,2)	1/3	(1/2,2/3.1/1)
strongly more important (SMI)	5	(3/2,2,5/2)	1/5	(2/5,1/2,2/3)
very strongly more important (VSMI)	7	(2,5/2,3)	1/7	(1/3,2/5,1/2)
absolutely more important (AMI)	9	(5/2,3,7/2)	1/9	(2/7,1/3,2/5)

Suppose a triangular fuzzy number A= $a_{ij}$is expressed as$[l_{ij}, m_{ij}, u_{ij}]$, i and j = 1,2…….n, where l_{ij}, m_{ij}, u_{ij} are the lower bound, the mean bound and upper bound of the triangular fuzzy set. In addition, we assume that $l_{ij} < m_{ij} < u_{ij}$when$i \neq j$.If $i = j$, then $a_{ij} = a_{ii}$=(1,1,1). Therefore, an exact priority vector $w = (\ w_1, w_2, \dots\dots\dots. w_n\ )^T$ derived from the judgement matrix must satisfy the inequalities.

Chang (1996) provided the following formula to calculate the synthetic value:-

$$\mathrm{a}_{\mathrm{ij}}^{\mathrm{t}} = [\mathrm{a}_{\mathrm{ij}}^{\mathrm{t}}, \mathrm{a}_{\mathrm{ij}}^{\mathrm{t}}, \mathrm{a}_{\mathrm{ij}}^{\mathrm{t}}],\ \mathrm{i,j} = 1,2, \dots, \mathrm{n_k},\ \mathrm{t} = 1,2, \qquad \text{4-14}$$

'T' is a TFN given by the t^{th} expert, by the formulak^{th}

$$M_{ij}^k = \frac{1}{T} \otimes (a_{ij}^1 + a_{ij}^2 + \dots + a_{ij}^T) \qquad \text{4-15}$$

The synthetic TFN of the k^{th} layer can be derived and the synthetic judgement matrix of the layer total factors towards the h^{th} factor of the

$(k-i)^{th}$ layer can also be obtained. Using the following formula (4-16) we can get synthetic degree value.

$$S_j^k = \sum_{j=1}^{n} M_{ij}^k \otimes \left(\sum_{i=1}^{n_k} \sum_{j=1}^{n_k} M_{ij}^k \right)^{-1},\ i = 1,2,\dots,n_k \qquad 4\text{-}16$$

The output of this sum $(\sum_{j=1}^{n} M_{ij}^k)$ is the fuzzy additional operation of n extent analysis values for a particular matrix such that:

$$\sum_{j=1}^{n} M_{ij}^k = \left(\sum_{j=1}^{n} l_{ij}, \sum_{j=1}^{n} m_{ij}, \sum_{j=1}^{n} u_{ij}\right) \qquad 4\text{-}17$$

The total some of these $[(\sum_{i=1}^{n_k} \sum_{j=1}^{n_k} M_{ij}^k)^{-1}]$, will lead to the fuzzy addition operation of $N_{ij}^k (j = 1,2,\dots,n)$ values such that, the inverse of the vector in equation (4-19) can be shown as follows: -

$$\left(\sum_{i=1}^{n_k} \sum_{j=1}^{n_k} M_{ij}^k \right)^{-1}, = \left(\sum_{j=1}^{n} l_{ij}, \sum_{j=1}^{n} m_{ij}, \sum_{j=1}^{n} u_{ij}\right)^{-1} \qquad 4\text{-}18$$

$$\left(\sum_{i=1}^{n_k} \sum_{j=1}^{n_k} M_{ij}^k \right)^{-1} = \left(\frac{1}{\sum_{j=1}^{n} u_{ij}}, \frac{1}{\sum_{j=1}^{n} m_{ij}}, \frac{1}{\sum_{j=1}^{n} l_{ij}}\right) \qquad 4\text{-}19$$

Once synthetic values are determined, the degree of possibility on one fuzzy number/synthetic value obtained to be greater than others is obtained as follows:-

$$V(M_1 \geq M_2) = \sup_{x \geq y}\left(\min\left(\mu_{M_1}(x), \mu_{M_2}(y)\right)\right) \qquad 4\text{-}20$$

$$V(M_1 \geq M_2) = 1 \text{ if } m_1 \geq m_2 \qquad 4\text{-}21$$

$$V(M_2 \leq M_1) = \text{hgt}\ (M_1 \cap M_2) = \mu_{M_1}(d) \qquad 4\text{-}22$$

$$V(M_2 \leq M_1) = \text{hgt}\ (M_1 \cap M_2) = \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} \qquad 4\text{-}23$$

Chang further added, the degree of possibility of i^{th} factor to be greater than others is as follows (Sarfaraz, et al. 2012).

$$V(M \geq M_1, M_2, \dots, M_k) = V(M \geq M_1) \text{ and } (M \geq M_2) \text{and} \dots \text{and } (M \geq M_k) =$$

$$\min V(M \geq M_i),\ i = 1,2,\dots,k \qquad \text{4-24}$$

Let

$$d'(S_i) = \min V(S_i \geq S_k) \qquad \text{4-25}$$

Hence the Weight Vector given by equation (4-26) (Saad et al 2015)

$$W' = (d'(S_1), d'(S_2) \dots\dots.. d'(S_n)\ )^T \qquad \text{4-26}$$

Where: - $S_i(i = 1,2, \dots..n)$are n elements of the matrix. The elements of each column are divided by the sum of that column and the elements in each resulting row are added and the sum is divided by the number of elements in the row), the normalized weight vectors are obtained as follows (Perçin 2008):-

$$W = (\ d(S_1), d(S_2), \dots, d(S_n)\ )^T, \qquad \text{4-27}$$

The final weight or global weight of each criterion is obtained by multiplying the criteria with the matrix obtained by calculating each alternative with respect of each criterion.

4.5.2 Converting the Rigid Matrix into Fuzzy Matrix

In the first step, the rigid matrix (table 4-2) is converted into the fuzzy matrix by the use of the fuzzy conversion Scale (4-10). Table (4-11) presents the converted matrix by the use of TFN for the main criteria (cost, availability, reliability and safety) and summarizes the sum of the rows, sum of the columns and the sum of the sum of the columns.

Once the sum of each rows and columns is obtained, the next step is to calculate the synthetic value extend. The synthetic extend of all criteria can be obtained by dividing lower bound of every row with the higher bound of sum of columns sum, middle bound of row with sum of columns sum and higher bound of the rows sum by lower bound of the sum of column sum.

Table 4-11: Fuzzy Comparisons Matrices for the Maintenance Main Criteria

Criteria	Cost	Availability	Reliability	Safety	Rows Sum
Cost	$(\frac{1}{2},\frac{1}{1},\frac{3}{2})$	$(\frac{1}{3},\frac{2}{5},\frac{1}{2})$	$(\frac{2}{5},\frac{1}{2},\frac{2}{3})$	$(\frac{1}{2},\frac{2}{3},1)$	(1.7 ,2.5 ,3.67)
Availability	$(2,\frac{5}{2},3)$	$(\frac{1}{2},\frac{1}{1},\frac{3}{2})$	$(\frac{1}{2},\frac{1}{1},\frac{3}{2})$	$(1,\frac{3}{2},2)$	(4,6,8)
Reliability	$(\frac{3}{2},2,\frac{5}{2})$	$(\frac{1}{2},\frac{1}{1},\frac{3}{2})$	$(\frac{1}{2},\frac{1}{1},\frac{3}{2})$	$(\frac{3}{2},2,\frac{5}{2})$	(4,6,8)
Safety	$(1,\frac{3}{2},2)$	$(\frac{1}{2},\frac{2}{3},1)$	$(\frac{2}{5},\frac{1}{2},\frac{2}{3})$	$(\frac{1}{2},\frac{1}{1},\frac{3}{2})$	(2.4,3.67,5.17)
Column Sum	(5,7,9)	(1.83,3.06,4.5)	(1.8,3.3,4.33)	(3.5,5.16,7)	
Sum of Column Sum (12.13,18.22,24.83)					

4.5.2.1 Synthesis

$$S_{\text{cost}} \left[\frac{1.7}{24.83},\frac{2.5}{18.22},\frac{3.67}{12.13}\right] = (0.068, 0.137, 0.302)$$

$$S_{\text{Availability}} \left[\frac{4}{24.83},\frac{6}{18.22},\frac{8}{12.13}\right] = (0.161, 0.329, 0.660)$$

$$S_{\text{Reliability}} \left[\frac{4}{24.83},\frac{6}{18.22},\frac{8}{12.13}\right] = (0.161, 0.329, 0.660)$$

$$S_{\text{Safety}} \left[\frac{2.4}{24.83},\frac{3.67}{18.22},\frac{5.17}{12.13}\right] = (0.097, 0.201, 0.426)$$

Once synthetic extend is determined the degree of possibility of fuzzy number/synthetic value obtained to be greater than other can determined by the following equations (4-23)–(4-25).

Synthetic values calculated for maintenance main criteria are shown below.

Comparison of S_{cost} with other synthetic values:-

$V(S_{\text{cost}} < S_{\text{Availability}})$

Mean value of cost (0.137) is not greater than mean value of availability (0.329) and lower bound of cost (0.068) is not greater than upper bound of availability (0.660) then, applying equation (4-23):-

$$V(S_{\text{cost}} < S_{\text{Availability}}) = \frac{(l_{Availability} - u_{cost})}{(m_{cost} - u_{cost}) - (m_{Availability} - l_{Availability})}$$

$$= \frac{(0.161 - 0.302)}{(0.137 - 0.302) - (0.329 - 0.161)} = 0.42$$

$V(S_{\text{cost}} < S_{\text{Availability}})$

Considering $S_{\text{Reliability}}$ has exactly the same value as $S_{\text{Availability}}$ so the same above calculation is applied which result into the same value of comparing $(S_{\text{cost}} \geq S_{\text{Availability}})$ which lead to $V(S_{\text{cost}} < S_{\text{Reliability}}) = 0.42$

$V(S_{\text{cost}} < S_{\text{Safety}})$

Mean value of cost is not greater than mean value of safety and lower bound of cost is not greater than upper bound of safety then, apply equation (4-23):-

$$V(S_{\text{cost}} < S_{\text{Safety}}) = \frac{(l_{Safety} - u_{cost})}{(m_{cost} - u_{cost}) - (m_{Safety} - l_{Safety})}$$

$$= \frac{(0.097 - 0.302)}{(0.137 - 0.302) - (0.201 - 0.097)} = 0.76$$

Comparison of $S_{\text{Availability}}$ with other synthetic values because the mean value of availability is greater than the mean value cost and safety and equal to the value of reliability so we follow equation (4-21):

$V(S_{\text{Availability}} = S_{\text{Reliability}}) = 1$, $V(S_{\text{Availability}} > S_{\text{cost}}) = 1$ and $V(S_{\text{Availability}} > S_{Safety}) = 1$

The mean value of reliability is equal to the mean value of availability and greater than the mean values of both cost and safety. Therefore, equation (4-21) is applied for reliability as followed:-

$$V(S_{\text{Reliability}} = S_{\text{Availability}}) = 1$$

$$V(S_{\text{Reliability}} > S_{\text{cost}}) = 1$$

$$V(S_{\text{Reliability}} > S_{Safety}) = 1$$

Comparison of S_{safety} with other synthetic values; because the mean value of availability is greater than the mean value cost and safety and equal to the value of reliability so we follow equation (4-21):-

$$V(S_{\text{Safety}} > S_{\text{cost}}) = 1$$

Mean value of safety is not greater than mean value of availability and lower bound of safety is not greater than upper bound of availability, and therefore equation (4-23) is applied:-

$$V(S_{\text{safety}} < S_{\text{availability}}) = \frac{(l_{availability} - u_{safety})}{(m_{safety} - u_{safety}) - (m_{availability} - l_{availability})}$$

$$= \frac{(0.161 - 0.426)}{(0.201 - 0.426) - (0.329 - 0.161)} = 0.67$$

$V(S_{\text{safety}} < S_{\text{Reliability}})$

Mean value of safety is not greater than mean value of reliability and lower bound of safety is not greater than upper bound of reliability, and therefore equation (4-23) is applied. As the synthetic value of reliability is equal to availability the same comparison with availability is performed and result into $V(S_{\text{safety}} < S_{\text{Reliability}}) = 0.67$.

Comparison of all the synthesis values of main criteria (cost, availability, reliability and safety) is performed and the minimum value of each element is taken in to account and the sum of each element are divided by the sum of the column which will give the priority of that element in the level. Then the normalized value can be obtained as per equation (4-26):-

$$W' = (\ 0.42\,,1\,,1\,,0.67 \ )^T$$

The next step now is to use equation (4-27) to normalizing the above value and the weights can obtain as follows:-

$$W_{cost} = \frac{0.42}{3.09} = 0.14$$

$$W_{Availability} = \frac{1}{3.09} = 0.32$$

$$W_{Availability} = \frac{1}{3.09} = 0.32$$

$$W_{safety} = \frac{0.67}{3.09} = 0.22$$

$$W_{main\ criteria} = (\ 0.14, 0.32, 0.32, 0.22 \ )^T$$

The abovementioned steps are applied to the rest of the matrixes that represents the pairwise comparison between the nodes with respect to the other node. Table (4-12) demonstrates the weights of criteria, sub criteria and local and global alternatives. The weight of the global alternatives is calculated and it is as followed (TBM=0.4, CBM=0.39 and CM=0.22).

Table 4-12: Criteria, Sub-Criteria and Alternatives Weights (TFN)

Main criteria %	Sub-criteria %	Local alternatives weight with respect to sub-criteria %	Alternative global weight %
cost 0.14	Pro-loss 0.33	TBM 0.389 CBM 0. 389 CM 0.223	TBM=0.40 CBM=0.38 CM=0.22
	Pro-damage 0.26	TBM 0. 389 CBM 0. 389 CM 0.223	
	Spare-parts 0.21	TBM 0.626 CBM 0.20 CM 0.174	
	Men-power 0.14	TBM 0.454 CBM 0.426 CM 0.119	
	E-maintenance 0.07	TBM 0.34 CBM 0.34 CM 0.32	
Reliability 0.32	MSI 0.468	TBM 0. 389 CBM 0. 389 CM 0.223	
	ATI 0.267	TBM 0. 389 CBM 0. 389 CM 0.223	
	MTBF 0.267	TBM 0. 389 CBM 0. 389 CM 0.223	
Availability 0.32	Inherent availability 0.40	TBM 0. 389 CBM 0. 389 CM 0.223	
	MTTR 0.26	TBM 0. 389 CBM 0. 389 CM 0.223	
	Availability on demand 0.34	TBM 0.43 CBM 0.39 CM 0.19	
Safety 0.22	Risk likelihood 0.35	TBM 0. 389 CBM 0. 389 CM 0.223	
	Environment 0.2	TBM 0. 389 CBM 0. 389 CM 0.223	
	Facility 0.23	TBM 0. 389 CBM 0. 389 CM 0.223	
	Personnel 0.22	TBM 0.43 CBM 0.34 CM 0.223	

Figure (4-15) demonstrates the outcomes of preferences in alternatives and their priorities with respect to the main goal (maintenance optimum strategy) by the use of FAHP. TBM is the first preferred priority with respect to the main goal with 40%, CBM comes second with 2% difference from TBM and the least preferred alternative (CM) comes last with 22%.

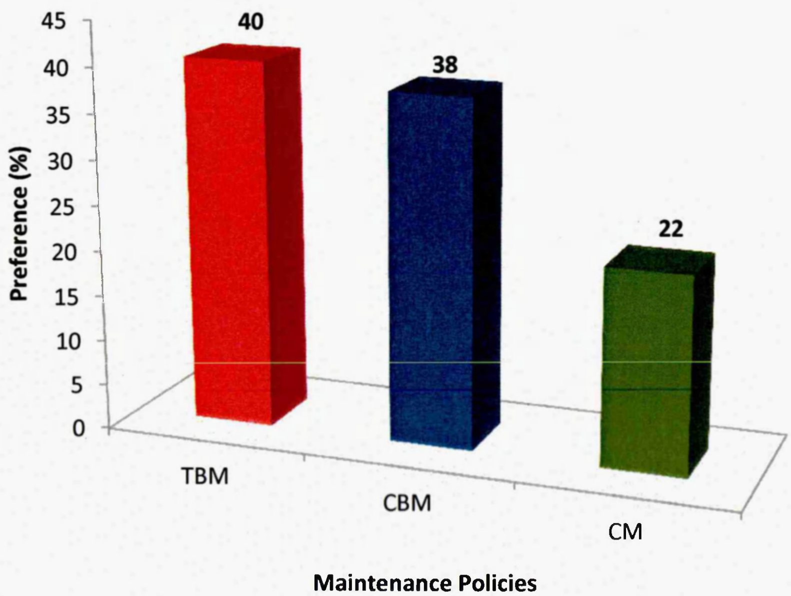


Figure 4-15: Alternative Preference with Respect To Main Goal (TFN)

4.6 Correspondence of Pairwise Matrix Evaluation Methods to Zero Consistency of Main Criteria Matrix

In this section, the sensitivity analysis is performed for all the applied derivation methods (MNV, NGM, EVM and TFN) by the selection of one matrix and equally adjusting the preferences and study the impact of this adjustment on the prioritization of alternatives cross the four derivations methods. The main criteria matrix is selected (table 4-2) and the consistency of this matrix is measured by Expert Choice (Consistency = 0.04).

Table (4-13) presents the priority of the main criteria (cost, availability, reliability and safety) for the four applied methods (MNV, NGM, EVM and

TFN) and the prioritization of the alternatives (TBM, CBM and CM) with respect to main goal (maintenance optimum policy).

Table 4-13: Criteria's Weight and Alternatives for Pairwise Matrix Evaluation

Derivation methods	Criteria				alternatives
	Cost	Availability	Reliability	Safety	
MNV	0.06	0.39	0.42	0.13	TBM= 0.47 CBM=0.439 CM=0.089
NGM	0.06	0.39	0.44	0.12	TBM=0.469 CBM=0.442 CM=0.088
EVM	0.091	0.362	0.392	0.156	TBM=0.472 CBM=0.440 CM=0.088
TFN	0.14	0.32	0.32	0.22	TBM=0.40 CBM=0.38 CM=0.22

The matrix of main criteria is adjusted by the use of Expert Choices function to arrive at 0.0 consistency. There are different scenarios that lead to the consistency to arrive at 0.0 within any matrix. The scenario which considered in this case study is the preference of the main criteria to arrive at the same preference that is obtained by FAHP, where reliability and availability are equally important.

The advantages of adjusting the main criteria matrix to have equal importance of availability and reliability are to studying the impact of this preference on the prioritization of the alternatives for the four methods. In addition to that, it allows studying the impact of the consistency's adjustment on FAHP and its derivation method TFN and how it would react to the adjustment.

The two main criteria preference (reliability and availability) have the same preference (32%) after applying TFN despite the fact that in the input rigid matrix there were slightly favoured preference towards reliability over availability. Therefore, the author wants to study the impact of the change in the matrix's consistency on both the classic methods (MNV, NGM and EVM) and on the conversion mechanism to TFN of the main criteria as well as the alternatives prioritization. Table (4-14) shows the adjusted matrix which has 0 consistency.

Table 4-14: The Maintenance Main Criteria Matrix with 0.0 Consistency

main criteria	Cost	Availability	Reliability	Safety
Cost	1	1/7	1/7	1/3
Availability	7	1	1	3
Reliability	7	1	1	3
Safety	3	1/3	1/3	1

Table (4-15) presents the preference of the main criteria with 0.0 consistency matrix and consequentially the impact of this adjustment on the prioritization of maintenance policies (TBM, CBM and CM).

Table 4-15: Main Criteria's Weights and Alternatives for Modified Matrix

Derivation methods	Criteria				Global weight of alternatives
	Cost	Availability	Reliability	Safety	
MNV	0.05	0.42	0.42	0.11	TBM= 0.465 CBM=0.439 CM=0.0899
NGM	0.05	0.41	.041	0.13	TBM=0.47047 CBM=0.44171 CM=0.08873
EVM	0.083	0.371	0.371	0.176	TBM=0.472 CBM=0.440 CM=0.088
TFN	0.144	0.316	0.316	0.224	TBM=0.405 CBM=0.381 CM=0.214

When the matrix consistency is zero which is the most preferable scenario mathematically, in this case, the reliability and availability would preferably have the same degree of preference towards the cost in the main matrix.

Figure (4-16) demonstrates the comparison between the preference of the main criteria (cost, availability, reliability and safety) as a result of adjusting the consistency to zero value.

The outputs of applying the derivation methods (MNV, NGM, EVM and TFN) show that when the entered data (availability and reliability are equally preferred) are applied, the preference of them is equally distributed.

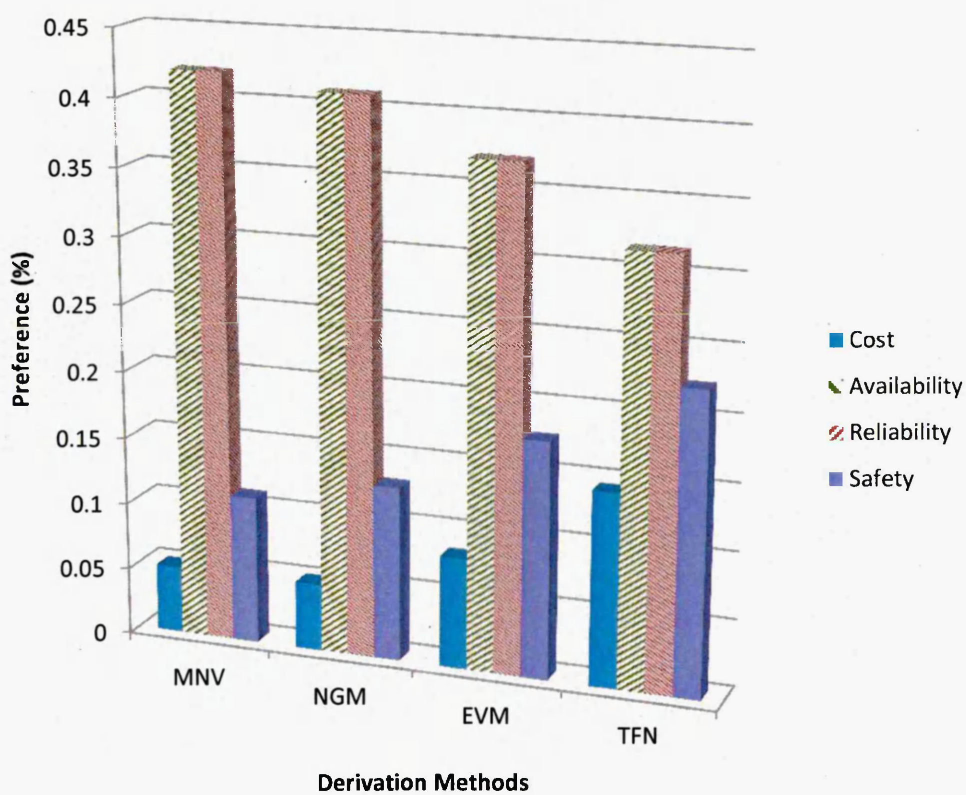


Figure 4-16: Main Criteria's Comparison Matrix (0 Consistency)

Figure (4-17) demonstrates the maintenance policy's priorities resulted from the four derivation methods with respect to main goal (0.0 consistency). The prioritization of the alternatives (maintenance policies) remains the same for all methods in terms of TBM as the most preferred alternative, CBM as second preferred and CM as the least preferred.

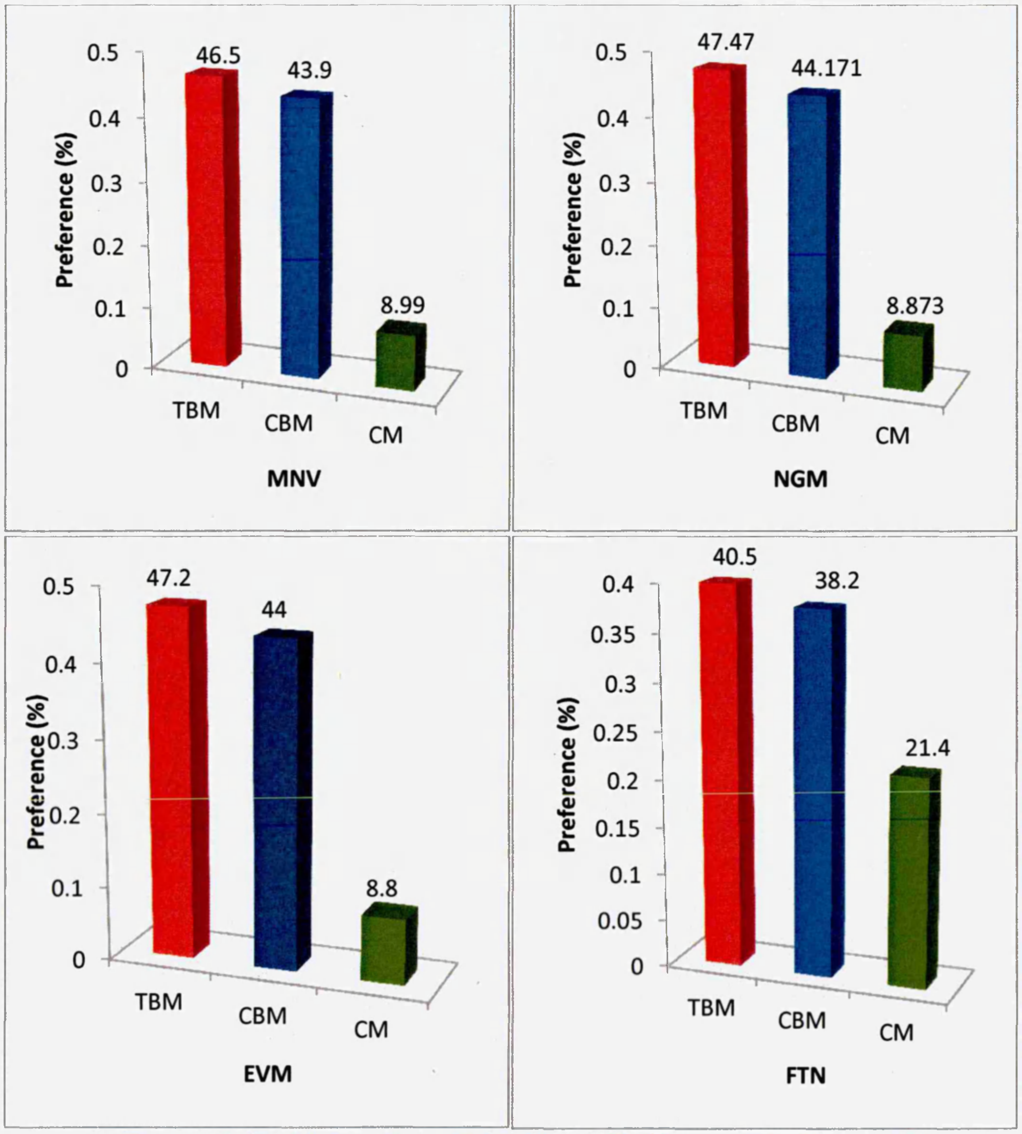


Figure 4-17: Alternatives Priorities with Respect to Main Goal

The alternative weights resulted from applying MNV remains almost the same in the case of CBM and CM. Whereas, slight change occurs in the weight of TBM which decreases by 0.5% following the change in the consistency (0.04 to 0.0).

The weight of CM and CBM using NGM remains the same with the change in the consistency, while the change of the prioritization of the other alternative TBM is increased by 14.7%.

The results of weights of alternatives using EVM remains the same despite the changes of the consistency, which is driven by the slight change in the preference in the rigid matrix.

The change in the preference of alternatives by the use of each derivation method following the slight adjustment in the matrix (preference of availability and reliability towards the cost to arrive at 0.0 consistency) is attributed to the way each method is conducted mathematically. NMV relies on the change of rows and the greater the change of the preference in the rows result into the change in the preference. The same conception applies to NGM, which considers the change in the rows and does not take into account the indirect change in the columns for which Saaty (1990) criticized the method, because of its non-conceptual justification for working with a logarithmic scale.

EVM has not shown much changes in the preference of the alternatives following the change of the consistency. This is can be attributed to the fact that EVM consider the indirect and direct change of the preference within the matrix. In other words, considering the change occurs in Table (4-2) and Table (4-14) in order to adjust the consistency, it is noticeable that the difference in the rows is substituted in the columns and due to this reason, the alternatives weight did not change much with EVM.

The preference in alternatives resulted from FAHP remains almost the same with the change of the consistency, which can be accredited to the fact that even when the original entered rigid matrix consistency was 4%, the result of the converted matrix led to equalizing the two main criteria (availability and reliability). Once the matrix was adjusted and both entered values of criteria were equalized (availability and reliability) in the original matrix, the same results were obtained which can be credited to the mathematical mechanism of the procedure of TFN.

4.7 Conclusion

In this chapter, the strategic level of the proposed integrated framework and the problem of selecting the most suitable maintenance policy and assigning it to equipment or its parts was discussed. The modelling of the problem using multi criteria decision making method (AHP) was applied and the structure of the criteria and sub-criteria that drive the decision-maker to select a particular maintenance policy and possible alternatives was identified for the petroleum industry.

AHP provided the advantage of considering all the relative factors by breaking out the structure of the hierarchy of the problem and considering all relevant factors associated with the petroleum industry such as reliability, availability, safety and cost. Different derivation methods (MNV, NGM and EVM) of classic AHP were applied and the results of each method have been listed and explained. Fuzzy analytic hierarchy process method was applied to the collected data to study the difference in deriving the weights between rigid methods and fuzzy values and utilize the advantages of TFN, which considers the uncertainty of the translation of the decision-maker's preference.

Sensitive analysis was performed on the four methods by adjusting the main criteria matrix to have 0.0 consistency and the effect of this action on the preference weight of the alternatives was explained. AHP has the advantage of permitting a hierarchical structure of the criteria, which provides users with a better focus on specific criteria and sub-criteria when allocating the weights.

The advantages of using AHP and FAHP was to decompose all possible factors that contribute to the selection of maintenance policies and the possible solutions (alternatives) were clearly notable. It is obvious that any change in the circumstances (weights of criteria and sub-criteria) would result in the change to some extent of the priority within the alternatives, which in this case will assist the maintenance team to respond quickly and more accurately to the change.

In conclusion, this chapter investigated the selection of maintenance policy (strategic level) by the use of AHP and FAHP and discussed the results and the comparison of different derivation methods for arriving at the selection of the most appropriate maintenance policy.

Chapter Five

Maintenance Operational Level

In this chapter, the proposed mathematical model is developed and applied on equipment within the oil and gas industry. The relative costs of maintenance within the petroleum industry are identified and defined to arrive at the identification of the optimum maintenance interval for equipment. Applications of the proposed model are applied on minor and major services to validate the mathematical model.

5.1 Introduction

Chapter Four discussed the selection of the most suitable maintenance policy by relying on classic and fuzzy analytic hierarchy process within the oil and gas industry. In the literature review, it is observed that the majority of the maintenance actions are scheduled on time and it is one of the most critical elements that the maintenance department within any petroleum companies are facing. The challenging aspect of the optimisation of preventive maintenance activities is to achieve a high performance in terms of operational availability, reliability, production stability and integrity of assets within the production line and decreasing the overall expenses of maintenance activities.

El-Jawhari and Collins (2014) suggested that the cost of maintenance are typically the third largest expenditure after raw material and energy costs. Moreover, IQPC (2014) stated that a well planned and executed annual shutdown will significantly reduce the risks of unforeseen downtime. Therefore, a mathematical model that considers the representation of the reliability, probability of failure and the maintenance costs is relied upon to optimise the maintenance intervals.

The balance between the costs of preventive and corrective maintenance action within the petroleum industry, taking into consideration the reliability through the presentation of failure probability is the main feature of the proposed mathematical model. This chapter is divided into two main parts:-

- Proposed mathematical model for maintenance scheduling.
- Application of the proposed model within the petroleum sector.

5.2 Proposed Mathematical Model for Maintenance Scheduling

Saad et al (2004) proposed a total maintenance cost equation (5-1) to calculate the total cost of maintenance to obtain an optimum time interval for maintenance activities within the manufacturing industry, which is also an intelligent mathematical model and considers the costs of equipment's maintenance and their reliability. Khalil et al (2009) developed the model and noted that the cost of the different types of maintenance (preventive and corrective) can be evaluated by considering the changes in the value of the actuation time. The increase of the actuation time increases the probability of failure $(F_{\Delta t})$. It is noted that from equation (5-1), an increase in actuation time also increases the cost of preventive maintenance (P_{mc}) and decreases the corrective maintenance cost(C_{mc}), which means that balancing the two costs will bring the total maintenance cost (TMC) to the optimum maintenance interval.

$$TMC = \frac{(Cmc * F\Delta t) + (P_{mc} * (1 - F_{\Delta t})}{T * (1 - F_{\Delta t})} \qquad 5\text{-}1$$

Where:-

$F_{\Delta t}$ Probability of failure (%).

P_{mc} Preventive maintenance cost ($).

C_{mc} Corrective maintenance cost ($).

T Time suggested by maintenance (hrs).

5.2.1 Probability of Failure $F\Delta t$

In the case of predicting the failure of components, probability distribution will be used. Different types of distributions are available with the use of Arena software which generate the entered data with different distributions and percentage of errors. However, Weibull distribution is mostly used in reliability model to represent the equipment lifetime (kelton et al., 2007) which is used in this study and equation (5-2) is the mathematical representation of the$F\Delta t$.

$$F_{\Delta t} = 1 - e^{-(\frac{t}{\beta})^{\alpha}} \quad 5\text{-}2$$

Where:-

α Shape parameter.

β Scale parameter.

5.2.2 Preventive Maintenance Cost (P_{mc})

Equation (5-3) demonstrates the major preventive maintenance costs. In addition to the rate and number of maintenance personals needed to complete the required work, time required for the completion of the task and the cost of spare parts, the probability of replacement (P_{rp}) of spare parts is considered here as well. Different factors lead to slight uncertainty of replacing the targeted parts such as, the condition of the maintained part and the operational hours.

P_{rp} is estimated using the condition of the part through its historical maintenance data and it increases if the historical data shows frequent replacement of the part or if it just requires some lubrication or so on. Because of the high cost of some of the spare parts, adding their cost to the equations is believed to result into different maintenance intervals, which is not the case all the time.

$$P_{mc} = \{\left(\sum_{i=1}^{n} C_{sp_n} \times P_{rp_n}\right) + \left(X_1 \times S_{mh} \times t_{ip}\right) + C_{wp} + C_{oh}\} \quad 5\text{-}3$$

Where:-

C_{sp} Cost of spare parts ($).

P_{rp} Possibility of replacing the part (%).

X_1 Number of maintenance personnel.

S_{mh} Maintenance personnel hourly rate ($/h).

t_{ip} Time spent by maintenance personnel in carrying out preventive action (hrs).

C_{wp} Waste disposable cleaning cost ($).

C_{oh} Cost of out-house maintenance ($).

5.2.3 Corrective Maintenance Costs (C_{mc})

The corrective maintenance cost's parameters are presented in equation (5-4). it is anticipated that the corrective maintenance cost will be more than the cost of preventive maintenance and that can be attributed to many reasons. For instance, corrective maintenance requires more time to identify, mobilise the resources and resolve the failure. In addition, the consequences of this failure on the machine itself, damages to the production and any possible delays and bottleneck at a particular production stage as a result, which always lead to the cost of corrective maintenance C_{mc} to be realistically higher than P_{mc}.

$$C_{mc} = \{(\textstyle\sum_{i=1}^{n} C_{sp_n} \times P_{rp_n}) + P_{LC} + Dc + B_{pc} + B_{LC} + C_{oh}\} \qquad 5\text{-}4$$

Where:-

C_{sp} Cost of spare parts ($).

P_{LC} Production losses cost ($).

Dc Damages cost ($).

B_{pc} Bottleneck penalty cost ($).

B_{LC} Booked labour costs ($).

Each of the elements of equation (5-4) is further explained in the following sections:-

5.2.3.1 Production Losses Cost (PLc)

PLc presents the possible losses in relation to the stoppage of the production line, considering the time needed to maintain and set up the machine as well as the department income and the production cycle time (equation 5-5)(Khalil et al 2009).

$$PLc = \begin{cases} (t_{ti} + t_{su}) \times \frac{\alpha}{\pi} & at\ t_{su} > 0 \\ \frac{t_{ti} \times \alpha}{\pi} & otherwise \end{cases} \qquad 5\text{-}5$$

Where:-

t_{ti} Production time loss excluding setup machine time (hrs).

t_{su} Machine set up time (hrs).

α Department's income due to one barrel ($).

π Production cycle time (hrs).

t_{ti} and t_{su} are considered separately because the time for setting up the machine which includes handing the machine over to the operation might take a long time and consequentially not considering this time would impact on the outcomes of the corrective cost.

5.2.3.2 Damages Cost (Dc)

Dc considers the damages that might occur as consequences of the failure. it also considers legal fines (Lc) imposed by the local authorities in case of environmental damages and the cost of cleaning non-hazardous and hazardous materials as a consequence of a failure which is very pertinent to oil and gas industry. Another additional related cost considered in equation

(5-6) is the cost of sequentially damaged parts/equipment as a consequence of the failure of another part/equipment and therefore the damage costs are represented in the following equation:-

$$\mathrm{Dc} = \{(\mathrm{V} \times C_{pd}) + \mathrm{Lc} + \mathrm{C}_{Wd} + C_{Sd}\} \tag{5-6}$$

Where:-

V Number of damaged production by barrel.

C_{pd} Value of damaged production ($).

Lc Legal fines in case of environmental damages ($).

C_{Wd} The cost of cleaning non-hazardous and hazardous materials ($).

$$C_{Sd} = \begin{cases} \sum C_{Sd} \\ 0 \quad otherwise \end{cases} \tag{5-7}$$

Where:-

C_{Sd} Cost of damaged parts due to failure of another part ($).

5.2.3.3 Bottleneck Penalty Cost ($\mathbf{B}_{Pc}$)

The bottleneck penalty cost emphasises the costs which are related to delay charges. Delay charges illustrate any fines incurred for the reason of delays in delivering the product at the scheduled time.

$$BPc = \begin{cases} \frac{(t_{ti}+t_{su})}{\pi} \times C_{pd} & at \quad C_{MT} < D_{FT} \\ \\ \frac{(t_{ti}+t_{su})}{\pi} \times C_{pd} + D_{Ch} & otherwise \end{cases} \tag{5-8}$$

Where:-

Dch Delay charges, which is further explained in equation (5-9).

C_{MT} Time required to complete corrective actions(hrs).

D_{FT} Due fine time (hrs) expresses the permissible time that is predefined between the supplier (petroleum companies) and buyers before the second party starts charging for the delays in delivery.

5.2.3.4 Delay charges (D_{Ch})

Dch as shown in the developed equation (5-9) considers the time required to complete corrective actions and D_{FT}.

$$D_{Ch} = (C_{MT} - D_{FT}) \times C_h \qquad 5\text{-}9$$

Where: - C_h Cost of delay charges per unit ($)

5.2.3.5 Booked Labour Costs (BLc)

BLc indicates to the related costs of maintenance labour and operational workers in terms of corrective maintenance (equation 5-10).

$$BLc = (X_1 \times t_{tc} \times S_{mh}) + (t_{ti} + t_{su}) \times S_{oh} \times X_2 \qquad 5\text{-}10$$

Where:-

t_{tc} Time spent by the maintenance personnel to repair failure(hrs).

S_{oh} Operator's hourly rate ($).

X_1 Number of maintenance personnel.

X_1 Number of operational personnel.

Therefore, the cost of corrective maintenance (C_{mc}) when all the terms are considered is represented in equation (5-11):-

$$C_{mc} = \Big\{ \Big(\sum_{i=1}^{n} C_{sp_n} \times P_{rp_n} \Big) + (t_{ti} + t_{su}) \times \frac{\alpha}{\pi} + (V \times C_{pd}) + L_C + C_{wd} + C_{sd} + \left(\frac{(t_{ti}+t_{su})}{\pi} \times C_{pd} \right) + (C_{MT} - D_{FT}) \times C_h + (X_1 \times t_{tc} \times S_{mh}) + (t_{ti} + t_{su}) \times S_{oh} \times X_2 \Big) \qquad \text{5-11}$$

5.2.4 Assumptions Considered for the proposed Model

For the adoption of the proposed mathematical model, a few assumptions have been made to reflect the reality of the problem:-

- Spare parts are available on site and the delay time of delivering them is negligible.
- Replacement of the parts depends on their condition.
- All calculations are made in US dollars ($).
- Maintenance technicians are well trained and able to carry out the work.
- Majority of the maintenance actions are carried out by the maintenances department within the company.

5.3 Applications of the Proposed Mathematical Method

Maintenance intervals between planned preventive maintenance services for the oil and gas field equipment are mostly made based on the recommendations of the manufacturer, as contained in their operation and maintenance manuals and followed by the maintenance department. The proposed model is applied on seven Ruston TA Turbines that act as a unit, which is installed in a downstream petroleum company and will remain anonymous for confidentiality reasons. Minor services for each of the Ruston TA Turbine are overtaken after 1500 hours of operation. However, the historical data and the experience gained over 40 years of running the Ruston Turbine TA, shows that the fuel filter, which is one of the parts replaced in the minor services will start to block at approximately 2000 hours of operation. The major overhaul for the Ruston Turbine carried out on the forth times of the minor overhaul (6000hrs). This service is scheduled to allow the replacement of certain parts and is pushed back for the purpose of carrying out both minor and major overhaul at the same time. The service is therefore cost-effective.

The application of the proposed mathematical model is organised as followed:

1. Calculating $P_{mc}$for minor services.
2. Calculating C_{mc} for minor services.
3. Computing the total maintenance cost for minor services.
4. Calculating $P_{mc}$for major services.
5. Calculating C_{mc} for the major services.
6. Computing the total maintenance cost for major services.

5.3.1 Preventive Maintenance Costs (P_{mc}) Minor Services

Pmc is calculated by the use of equation (5-3). Table (5-1) shows the spare parts costs, the probability of replacement of each part Prp (which is estimated based on the historical data of replacement parts) and the quantity of each of the spare parts (QTY).

Prp of the oil burner was estimated by finding out the number of times that maintenance replaced the part and divided this by the number of maintenance services conducted including the time when the part was not replaced.

Table 5-1: Costs of Spare Parts for Minor Services

Part name	Quantity	Prp (%)	Unit Price ($)
Oil burner	1	5	6413.63
Filter	4	100	264
Cleaning agent	2	100	23.64
Total C_{sp}		$1425.642	

The associated costs of preventive maintenance action for minor services are illustrated in table (5-2) including the number of maintenance personnel required to perform the task and their wages, which may fairly vary from one region to another.

Table 5-2: Preventive Maintenance Costs for Minor Services

Variable	Value and Units
C_{sp}	$1425.642
X_1	2
S_{mh}	$25
t_{ip}	18 hrs
C_{wd}	$100
P_{mc}	$2425.642

5.3.2 Corrective Maintenance Costs (C_{mc}) Minor Service

In the case of CM, the required quantity of each spare part as well as the possibility of replacing each part remains the same (Table 5-1). As a consequence of the failure, however, it would damage the compressor rotor which is a high cost component. In addition to that, the number of maintenance technicians in the case of CM, as well as time required to complete the job is increased. Table (5-3) presents the costs involved in CM actions. All associated costs are substituted in equation (5-10) to extract the corrective maintenance cost for minor services, which is represented at the last row in table (5-3).

Table 5-3: CM Relevant Costs for Minor Service

Variable	Values and Units
C_{sp}	\$1425.642
X_1	3
S_{mh}	\$25
t_{ic}	66 hrs
C_{wd}	\$200
c_{sd}	\$205,709.14
C_{mc}	\$212284.78

5.3.3 Total Maintenance Cost for Minor Service

The value of C_{mc} (\$212284.78) is multiplied by the probability of failure and the value of P_{mc} (\$2425.642) is multiplied by the survival factor (1- $F\Delta t$) to illustrate the behaviour of both costs. The behaviour of both costs is impacted by the probability of the failure and the survival factor. Figure (5-1) demonstrates the behaviours of Cmc towards $F\Delta t$ and the increase in the corrective cost with time.

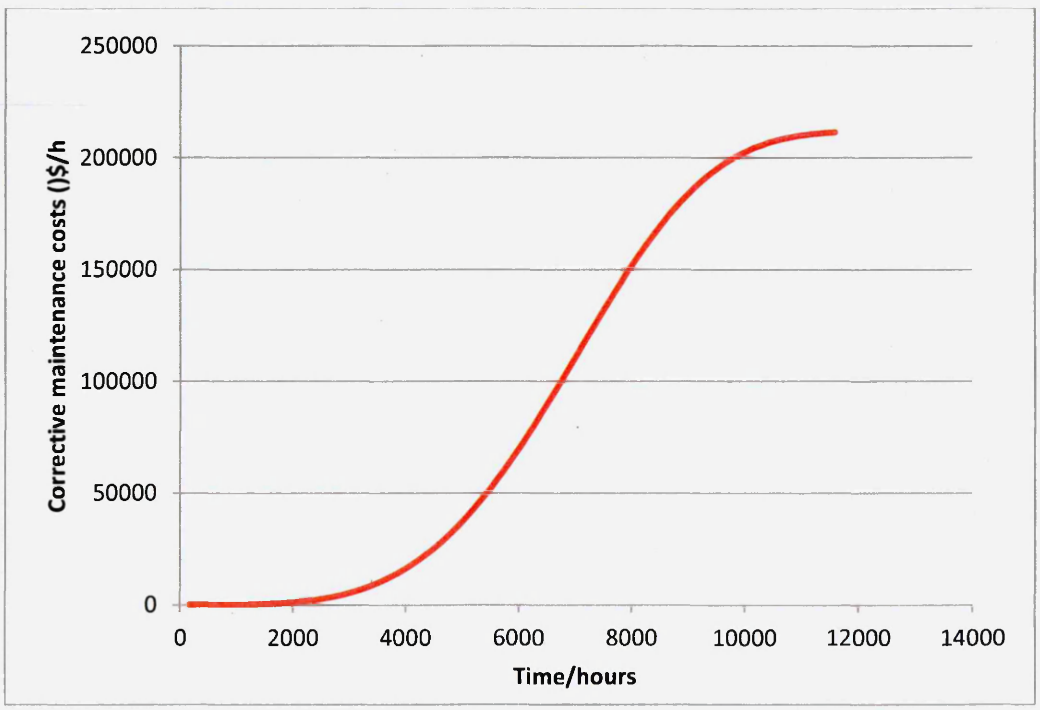


Figure 5-1: The Behaviour of $(Cmc \times F\Delta t)$ for Minor Service

Figure (5-2) demonstrates the behaviour of the preventive maintenance costs multiplied by the survival factor (1- $F\Delta t$). It is notable that Pmc decrease with the time and this is attributed to impact of the decreased survival factor.

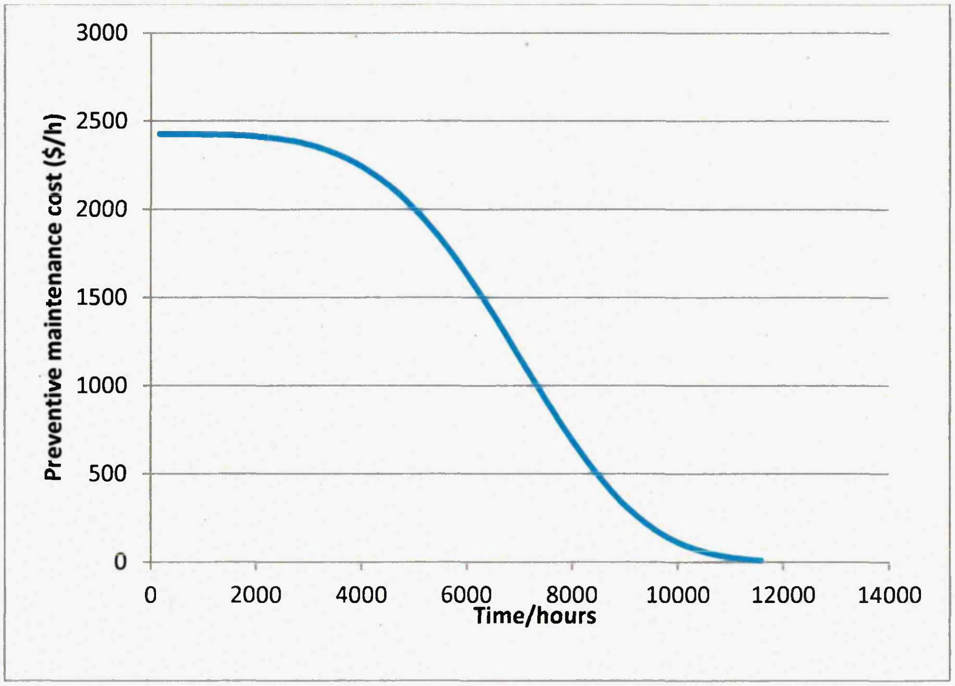


Figure 5-2: The Behaviour of ($Pmc \times (1 - F\Delta t)$) for Minor Service

Equation (5-1) is applied and the values of C_{mc} and P_{mc} for minor services are substituted. Table (5-4) presents the total maintenance cost including $C_{mc}$and $P_{mc}$and its development within the time (hrs).

Table (5-4) contains two categories: time in hours and the TMC ($/h). It shows the gradual decrease in the total cost of maintenance with time at the beginning of the computation until it arrives into the lowest possible cost. It then starts increasing again to arrive at the highest cost where the probability of the failure is 100% and the survival factor is equal to zero. The lowest maintenance cost occurs at 1848 hours of operation with a minimum cost of 289.45 $/h.

Table5-4: TMC for Minor Service ($/h)

Time (hrs)	TMC ($/h)	Time (hrs)	TMC ($/h)
168	2425.692586	1848	289.5404499
336	1213.225684	2016	291.820029
504	809.945107	2184	300.7210948
672	609.723812	2352	315.9814478
840	491.6000037	2520	337.5124219
1008	415.4575129	2688	365.351488
1176	364.2822125	2856	399.6332154
1344	329.7241611	3024	440.5717385
1512	307.2855022	3192	488.4507988
1680	294.3962589	3360	543.6190597

Figure (5-3) demonstrates the behaviour of the total maintenance cost. Total maintenance cost starts at $2425.692586 and gradually drops to the lowest cost (which is considered as the maintenance interval) and increases again following the impact of failure probability increment and the survival factor.

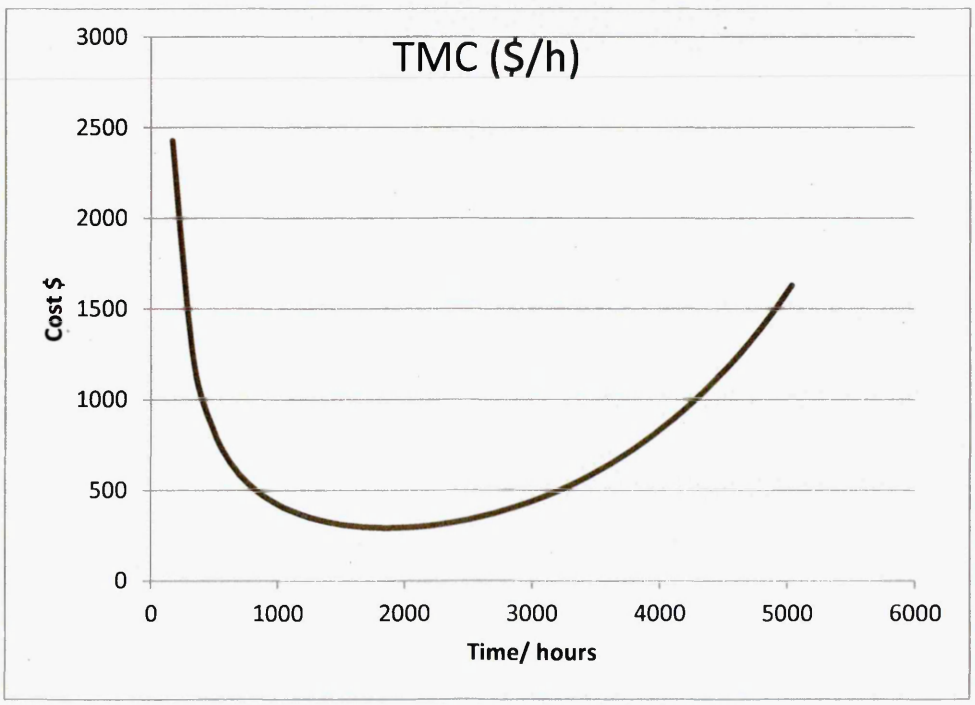


Figure 5-3: TMC ($/h) for the Minor Service

5.3.4 Preventive Maintenance Costs P_{mc} Major Service

Table (5-5) presents the spare parts prices and the possibility of replacement for each part according to the collected historical data from the maintenance department. These percentages are used to estimate the probability of replacing the parts, according to the historical data of the part movement, and do not represent the probability of the failure.

Table 5-5: Spare parts Cost for Major Service

Part name	Quantity	P_{rp} %	Unit Price ($)
Filter lube element	1	100	470.37
Igniter plug	1	50	812.18
Fuel pump	1	60	2173.97
Total C_{sp}		$2180.842	

Table (5-6) illustrates the related costs that involved in PM actions. The cost of PM for major service is obtained by using equations (5-3) and is result to P_{mc}= $3280.842.

Table 5-6: Preventive Maintenance Costs for Major Service

Variable	Values and units
C_{sp}	$2180.842
X_1	2
S_{mh}	$25
t_{ip}	20 hrs
C_{wd}	$100

5.3.5 Corrective Maintenance Costs Cmc Major Service

The quantity of spare parts remains the same for the major services planning in the case of corrective actions, but in the case of the occurrence of the failure, the possibility of replacing the listed parts are going to be certain because of the failure (Table 5-7).

Table 5-7: Spare parts Cost for Major Service

Part name	Quantity	P_{rp} %	Unit Price ($)
Filter lube element	1	100	470.37
Igniter plug	1	100	812.18
Fuel pump	1	100	2173.97
Total C_{sp}		$3456.52	

The consequences of the failure will certainly lead to the damage of the compressor rotor which costs " $205,709.14 ", and therefore this cost is considered as main element of C_{mc}. Table (5-8) demonstrates the related cost of CM actions and by applying equation (5-11), the total cost of corrective maintenance is calculated (C_{mc} = $214540.66).

Table 5-8: Preventive Maintenance Costs for Minor Services

Variable	Values and units
C_{sp}	$3456.52
X_1	3
S_{mh}	$25
t_{ic}	68 hrs
C_{wd}	$200
c_{sd}	$205,709.14

5.3.6 Total Maintenance Cost for Major Service

The corrective and preventive maintenance costs are calculated" $214540.66, $3280.842" respectively. Figure (5-4) shows that the occurrence of corrective maintenance costs less for the maintenance department as the probability of failure at infant age is relatively small (1.13463×10^{-5}) and increases as the part ages to arrive at the maximum price because the probability of the failure reaches 100%.

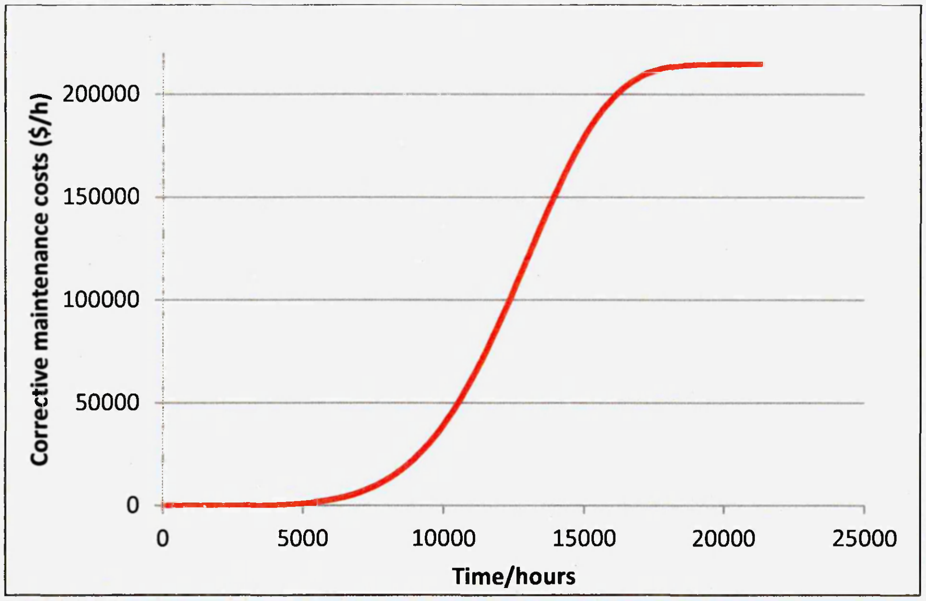


Figure 5-4: The Behaviour of ($Cmc \times F\Delta t$)for Major Service

The survival factor drives the value of P_{mc} at the highest value as the survival factor is at the highest value (100%) at an early life of the part. This is attributed as the cost of carrying out preventive maintenance in early stage and results to costing the maintenance department unnecessary spending considering the high percentage of the survival factor as shown in figure (5-5).

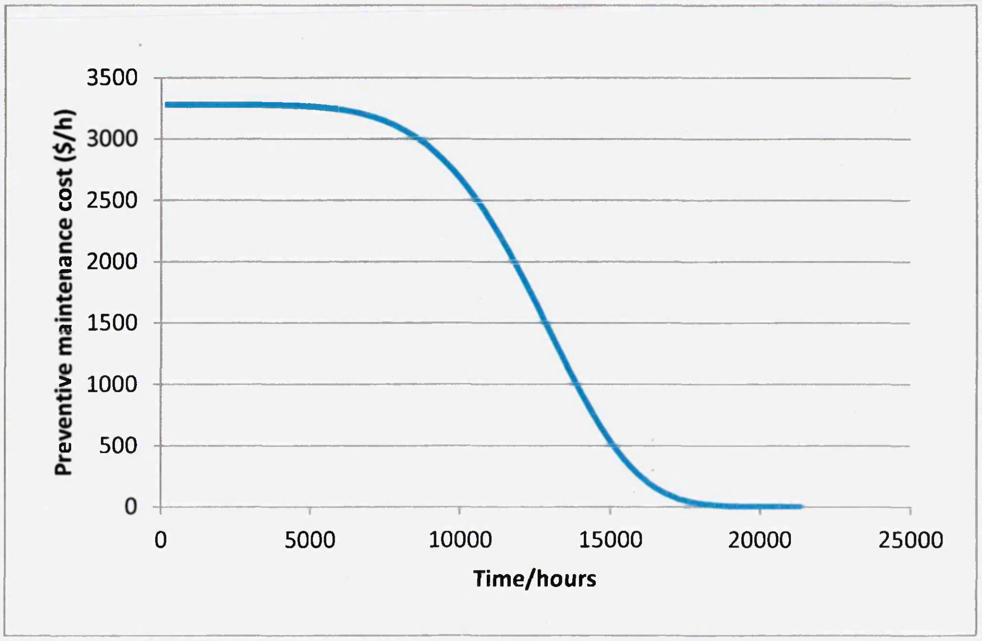


Figure 5-5: Behaviour of $P_{mc}$for Major Service

Table (5-9) presents the results of total maintenance cost obtained from applying equation (5-1). The values of TMC are listed to recognize the optimum time interval for the maintenance to be planned (The complete table appendix C).Total maintenance cost for the major activities starts high at 3280.842 \$/h, and decreases to reach an interval between the weeks 43-47.

Table 5-9: TMC for Major Service (\$/h)

Time(hrs)	TMC (\$/h)	Time(hrs)	TMC (\$/h)	Time (hrs)	TMC (\$/h)
168	3280.842	4872	112.7902828	9576	146.0025517
504	1093.613978	5208	105.4501135	9912	181.9335769
840	656.1681936	5544	99.0463575	10248	231.611416
1176	468.6908071	5880	93.4779416	10584	299.2119455
1512	364.53526	6216	88.70490222	10920	390.0506423
1848	298.2517447	6552	84.7516394	11256	510.8842933
2184	252.3586869	6888	81.71630427	11592	670.3091787
2520	218.697055	7224	79.78638882	11928	879.2977697
2856	192.946391	7560	79.26102628	12264	1151.937923
3192	172.6045316	7896	80.58086886	12600	1506.472669
3528	156.1220148	8232	84.36674377	12936	1966.792191
3864	142.4885045	8568	91.46864358	13272	2564.614456
4200	131.018363	8904	103.027031	13608	3342.727542
4536	121.2324673	9240	120.5489927	13944	4359.890134

As shown in figure (5-6) the minim total maintenance cost occurs between the week 43 and the week 46 and the lowest values of TMC occurs at week 45 (7560 hrs) . For simplicity, not all data was plotted and to have a clear capture of the decrease and increase of TMC.

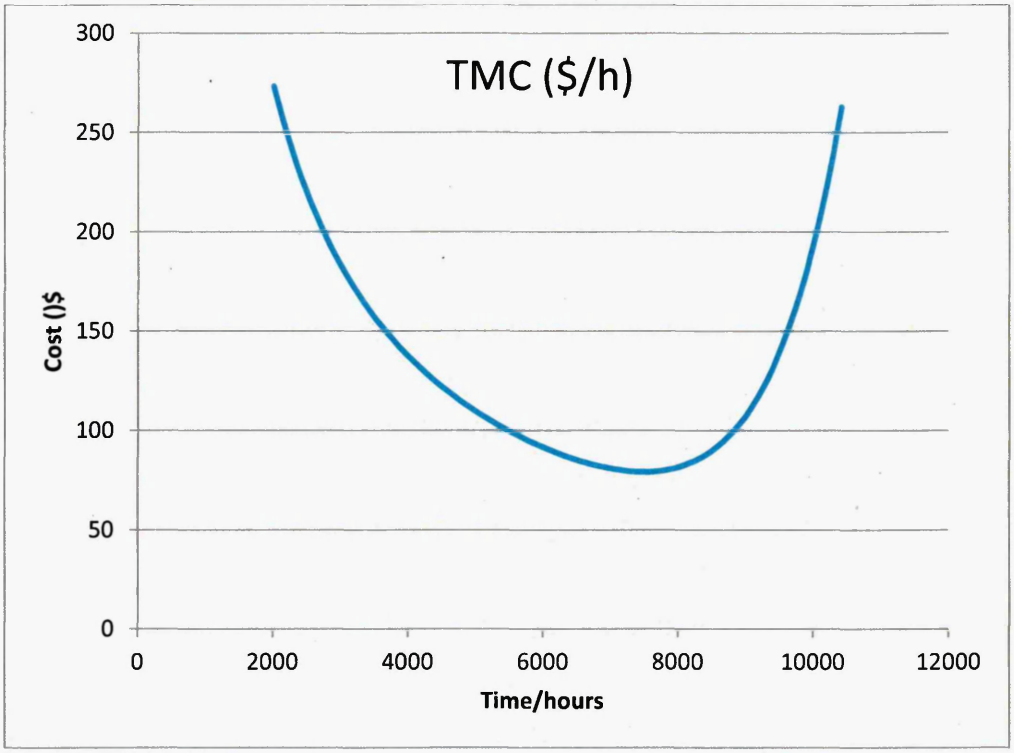


Figure 5-6: TMC ($/h) for Major Services

5.3.7 Scheduling PM Intervals for Ruston Turbine

The optimum maintenance time for minor service to be carried out was calculated at 1848hrs (11 weeks) and for major services at 7560hrs (45 weeks). For utilization of the resources and decreasing the interruption of operation, major maintenance is recommended to be pushed back and carried out on week 44 (7392hrs) instead of week 45 in order to opportunistically perform the fourth minor maintenance simultaneously with major service's first interval.

5.3.8 The Proposed Model's Cost Effectiveness

The implementation of the proposed mathematical model achieved promising results in regards to identifying preventive maintenance intervals instead of following the manufacturer recommendations.

The current maintenance interval for minor service is scheduled at 1500hrs resulting into the maintenance to be planned for five times a year. The outcomes of the proposed model improves the scheduling of maintenance intervals by shortening the mean time between maintenance (MTBM) into 4 times a year instead of performing maintenance 5 times a year.

The above calculations are made for one turbine, assuming that the other turbine's failure mechanisms are identical. The impact of the proposed model on scheduling the PM activities is highly positive, reducing the total maintenance cost (TMC) on yearly bases The preventive maintenance is calculated to be $2425.642 for five times a year. Thus, for the seven turbines the total saving comes from $12128.21 to $9702.568 without compromising on the reliability of the equipment (figure 5-7).

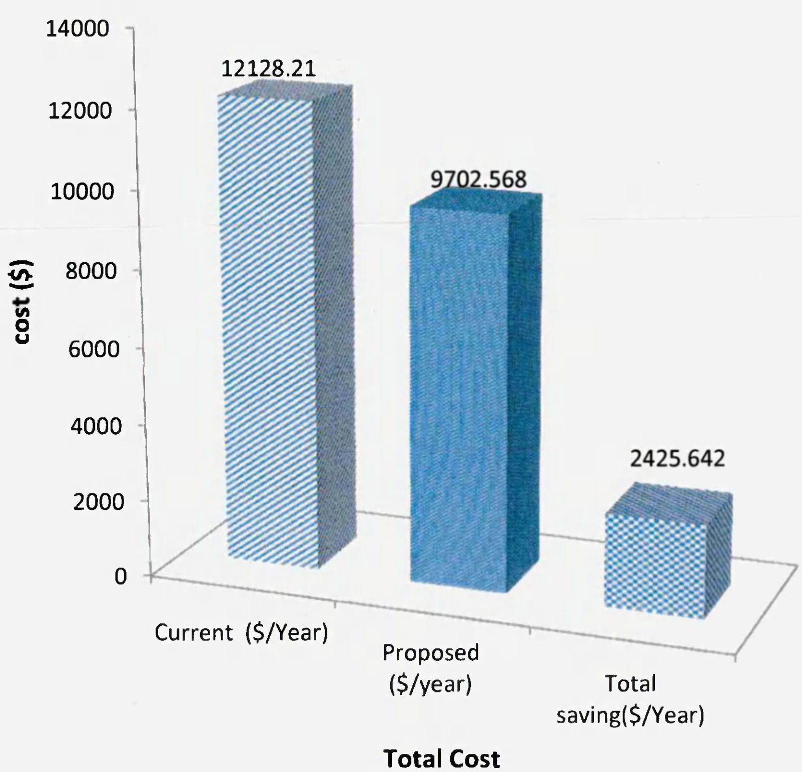


Figure 5-7: Total Cost Saving ($/year) For Minor Service

The major service for the Ruston Turbine TA is conducted each 6000h according to the current manufacture recommendations. However, historical data shows that the failure of maintained parts occurs at approximately 7500hrs. The outcome of the developed model suggest that maintenance should be carried out at 7392hrs.The model proved that it is possible to extend the mean time between maintenance without impacting on reliability of equipment. Over a period of three and half years, maintenance activities cost for major service are reduced and the total saving of maintenance cost increases to reach $3148.41 (figure 5-8).

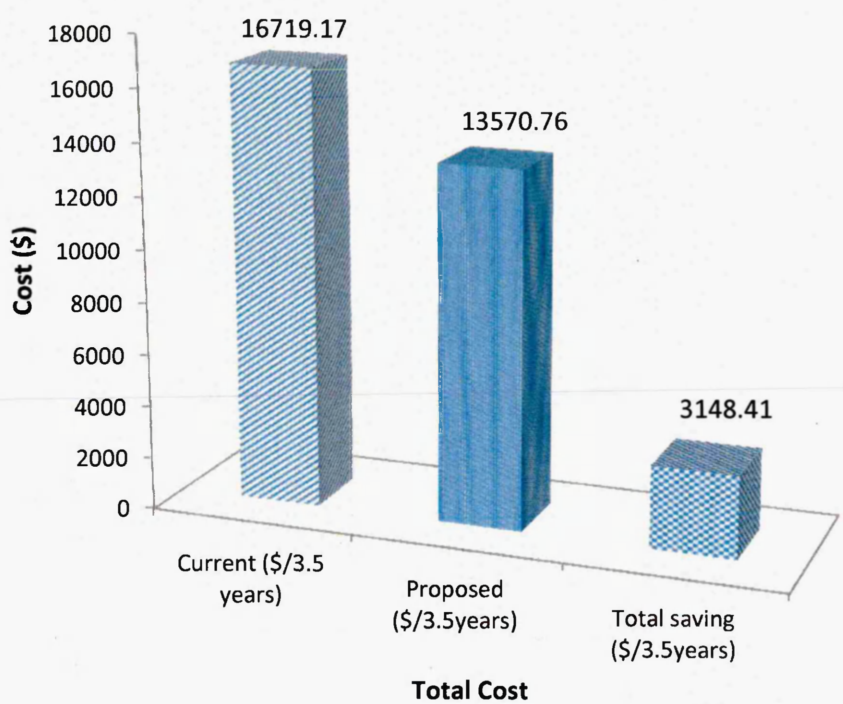


Figure 5-8: Total Cost Saving ($/3,5year) Major Service

The identification of the associated costs with both corrective and preventive maintenance activities have its advantages, besides obtaining the optimum time to maintain equipment. The ratio between preventive and corrective maintenance cost indicates the appropriateness of the selected maintenance policies for that particular equipment. Higher the ratio of Cmc to Pmc, the more suitable the decision of PM for that particular part becomes from a cost point of view. Otherwise more investigation is needed to be performed with regards to reasons of selecting PM for that part.

Analysis of the cost elements significantly improves the understanding of the main costs of CM and PM. The elements of involved costs suggest that the impact of wrongly selected maintenance schedule harms the equipment in the selected case study and unless stand by turbines are installed, the operational damages would increase the cost of corrective maintenance.

5.3.9 The Impact of the Proposed Model on Operation Availability

Operation availability is the portion time that the equipment is in good condition to fulfil its function (Márquez 2007). Optimising preventive maintenance scheduling has a positive impact on the operational availability (OA) of the equipment. Operational availability of equipment is driven by the mean up time between maintenance and mean down time (MDT) activities equation (5-6).

$$OA = \frac{MUT}{MUT+MDT} \qquad 5\text{-}12$$

Where:-

MUT Mean up time between failures.

MDT Mean down time between failures.

The percentage of operational availability for the minor services is calculated on the assumption that the current MUT is 1500hrs, and the MDT is equal to the time required to repair the machine (18 hrs). The same MDT is assumed for the proposed OA but the MUT is 1848hrs (figure 5-9).

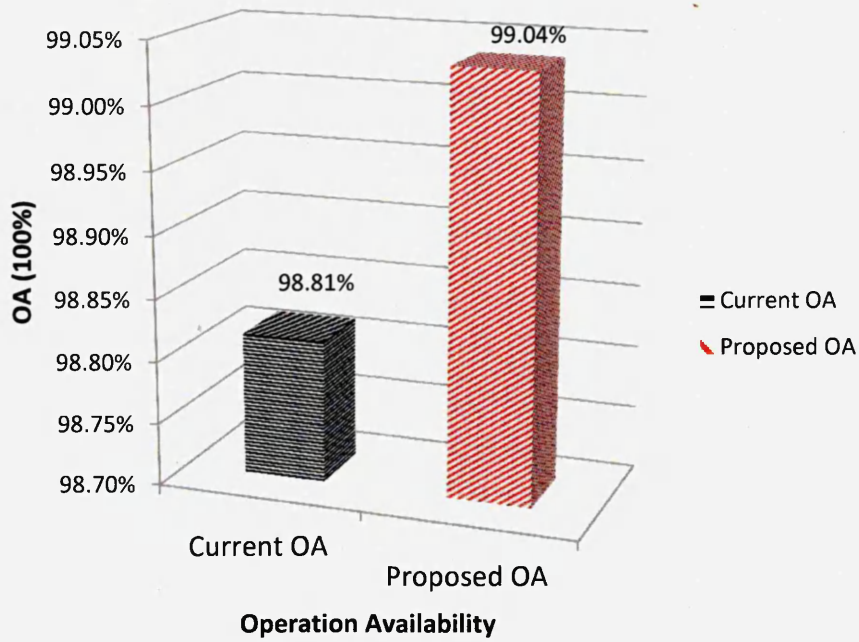


Figure 5-9: Improved OA for Minor Service

Figure (5-10) which compares current OA and the improved OA for major services with the assumption that MUT is 6000h and 7560hrs for the current and the proposed services respectively, and MDT is equal to the time required to repair the machine (86hrs).

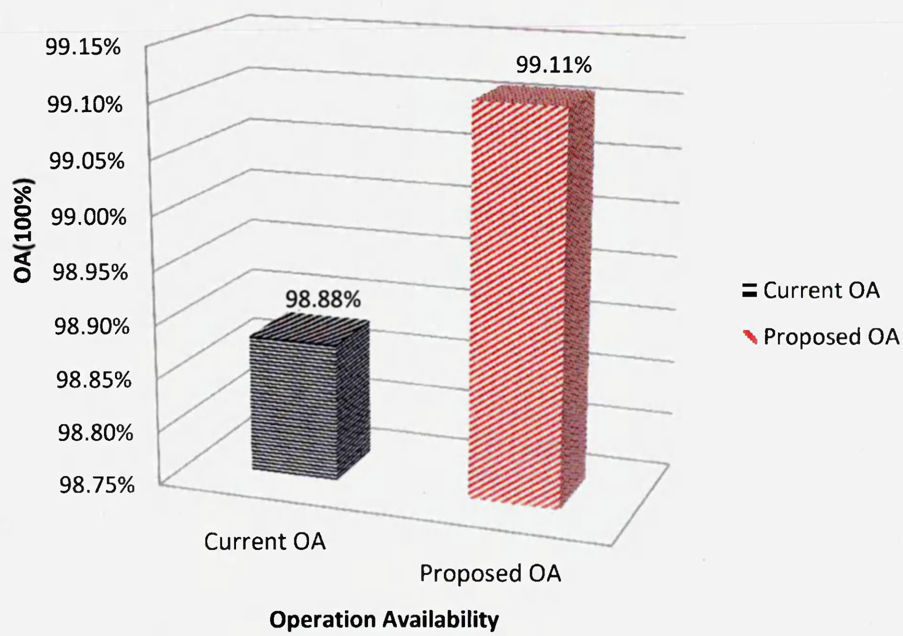


Figure 5-10: Improved OA for Major Service

5.3.10 Sensitivity Analysis of the Proposed Model

In this section, the sensitivity analysis is performed to understand the correspondence of the model to the change of preventive and corrective maintenance costs. To validate this analysis, the assumption is made to have the same failure distribution. The two proposed scenarios consider that preventive maintenance cost is equal to the corrective maintenance cost in the first case and the PM cost is higher than CM cost in the second case.

5.3.10.1 Costs of PM and CM Presumably Equal

The sensitivity analysis it applied to examine the response of TMC to the change and to check if the mean time between maintenance increases or decreases following the change. In this assumption, both costs are equal ($212374.7) and the probability of failure remains the same. In this case as shown in table (5-10), the optimum maintenance interval is increased from 11 weeks to 32 weeks (5376hrs).

Table 5-10: TMC ($/h) for Minor Services under (PM=CM Costs)

T(hrs)	TMC ($/h)	T(hrs)	TMC ($/h)	T(hrs)	TMC ($/h)
168	212374.6482	2688	13487.25815	5376	8581.25056
504	70792.96503	3024	12104.53783	5544	8593.873315
840	42481.41434	3360	11041.25085	5880	8749.131326
1176	30357.01231	3696	10220.92015	6216	9065.509272
1512	23634.97461	4032	9594.662737	6552	9573.112833
1848	19375.84769	4368	9131.191614	6888	10317.94956
2184	16450.69698	4704	8811.352133	7224	11368.86935
2352	15312.40319	4872	8701.867045	7392	12039.50054
2520	14334.19075	5040	8625.178427	7560	12828.76195

This emphasizes the importance of including the costs of hazards and cleaning the environment within the developed model because if they were not included and the cost of PM and CM were equal, then the consequences of failure would be catastrophic.

5.3.10.2 Cost of PM Higher Than Cost of CM

The second proposed scenario is the case where the PM cost was found to be higher than the cost of CM. The preventive maintenance cost was assumed to be twice as high as that of the corrective maintenance cost ($424749.4) and correspondingly, the optimum interval was increased consequentially (37 weeks) as shown in Figure (5-11).

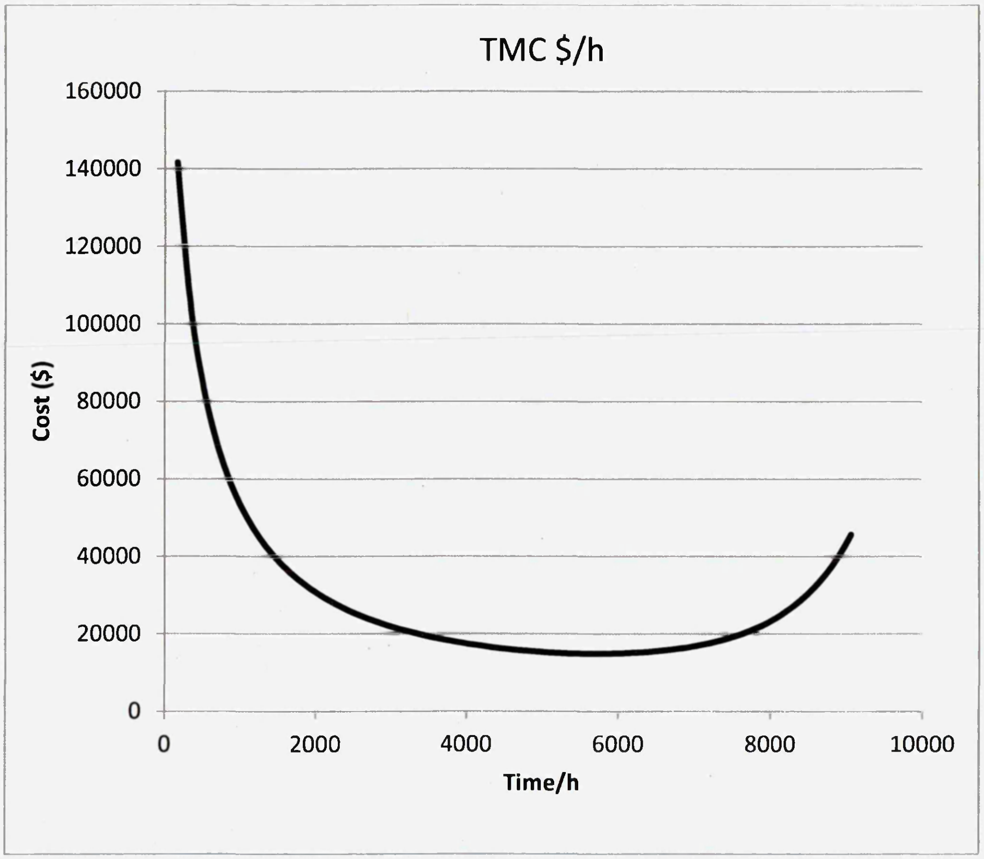


Figure 5-11: PM Cost Higher than CM Cost for Minor Services

5.4 Conclusion

In this chapter, the difficulty of scheduling preventive maintenance activities for equipment within the oil and gas industry has been discussed. A development of equations for costs of both corrective and preventive maintenance were also presented. These equations were modified to simulate the major costs involved in the maintenance activities within the oil and gas industry including the probability of replacement the part, fees of delay, cost of environmental cleaning and out-house maintenance cost.

The outcome of the mathematical model shows promising results in terms of reducing the cost of maintenance activities without compromising on the reliability of the assets.

The results were compared to the historical data with regards to the failure history to ensure that the advised maintenance interval time is within enough time as per the possibility of the occurrence of the failure and all obtained results were encouraging. Notable improvement in the operation availability of the equipment is achieved by the implementation of the proposed model in comparison to the current maintenance state.

The sensitivity analysis proved the importance of the developed costs to simulate the real scenario by showing the impact of the changes to the cost of PM and CM. The results showed that higher the cost of PM over the cost of CM, the longer the mean time between maintenance will be. The logical explanation of the sensitivity analysis suggested that if CM costs were less than PM costs, then it is more likely to run the part to failure. This stresses on the importance of embodying the relevant costs that has been ignored in other models such as the cost of delay.

To sum up, the proposed mathematical model attempted to answer the questions with regards to calculating the optimum time to conduct preventive maintenance and the applications of the model showed improvement in equipment's reliability and availability with decrease in the maintenance expenditures.

Chapter Six

An integrated Approach between Maintenance and Spare Parts Control

Chapter Six presents the integrated approach between optimum preventive maintenance interval and spare parts control. The relation between preventive maintenance and inventory department is demonstrated and as well as the proposed approach including the relevant equations. Applications of the proposed approach are demonstrated to validate the applicability of the approach. The results are finally listed at the end the chapter.

6.1 Introduction

Chapter (5) dealt with the optimisation of preventive maintenance interval and a mathematical model was proposed and applied to obtain the optimum interval to maintain equipment within the petroleum industry. In this chapter, an integrated approach between spare parts management and preventive maintenance is developed to minimise total inventory cost.

The high cost of spare parts of the equipment within the petroleum industry drives the need for optimisation of the inventory management in the industry. The high responsiveness required due to downtime costs and the risk of stock obsolescence drives the need to address this particular matter (Cohen et al 2006).

Bacchetti et al 2010 stated that Keeping the appropriate stock quantity of spare parts to cover the demand when preventive maintenance is executed and avoiding disturbance to operations due to delay of shortages in spare parts as an important issue. The proposed approach focuses on the integration between the developed mathematical model to optimise preventive maintenance intervals, which is described in Chapter Five and the inventory management for the spare parts to be delivered or stocked to guarantee its availability at the right time to perform maintenance at the planned time.

This chapter is divided into two main sections:-

- Methodology and proposed integrated approach
- Application of the proposed integrated approach

6.2 Methodology and Proposed Integrated Approach

In a bid to accommodate the function of inventory, companies maintain four types of inventories and they are: raw material inventory (RMI), which refers to material used in the production process that has not been processed yet (Eroglu and Hofer 2011); work-in-process inventory (WIP), which refers to material that has been processed but not completed yet; finished goods inventory (FGI), which are the completed items that ready to be sold but still an asset on the company books and finally maintenance, repairs and operations inventory (MRO) which refers to spare parts required to ensure production can be continued (Heizer and Render, 2014).

The nature of the petroleum industry suggests that MRO inventory required to keep the operation running has the highest proportion in terms of cost within the inventory management department. This emphasises the importance of optimising the activity of inventory management and controlling the spare parts to ensure a satisfactory level of inventory for PM requirements. Optimising the spare parts refers to the shortages and overstocking of spare parts which should be avoided to control costs and ensure the security of the capital of the company.

Figure (6-1) demonstrates the proposed integrated approach to optimise and control spare parts. This approach relies on the optimisation of the maintenance interval and obtaining the required information and processes the time between intervals as the lead time to deliver the spare parts by the inventory department. The integrated approach does not consider the spare parts required for the corrective maintenance, it is only applied in the case of planned maintenance activities.

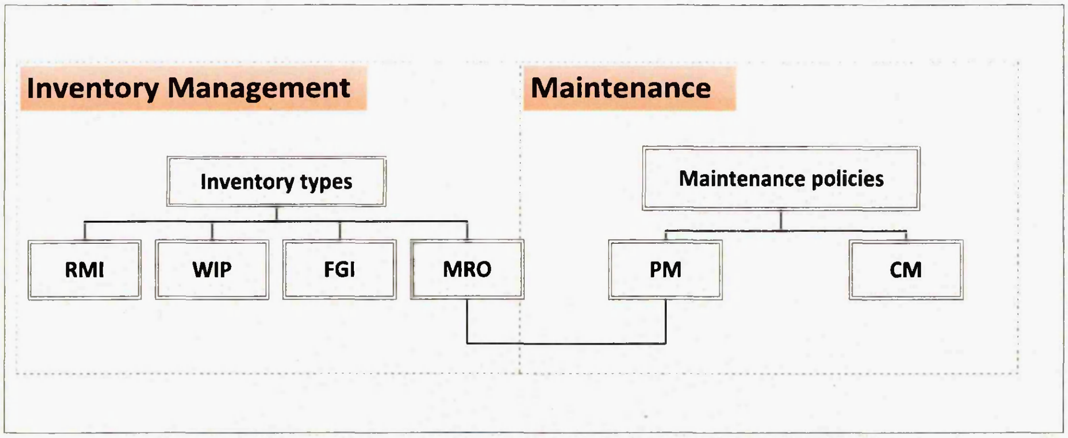


Figure 6-1: The Integrated Maintenance and Inventory Approach

Figure (6-2) presents the description of the process taken to arrive at the determination of economic order quantity, reordering point and the safety stock of spare parts. It demonstrates the relationship between PM optimisation process and its interaction with the process of controlling the spare parts.

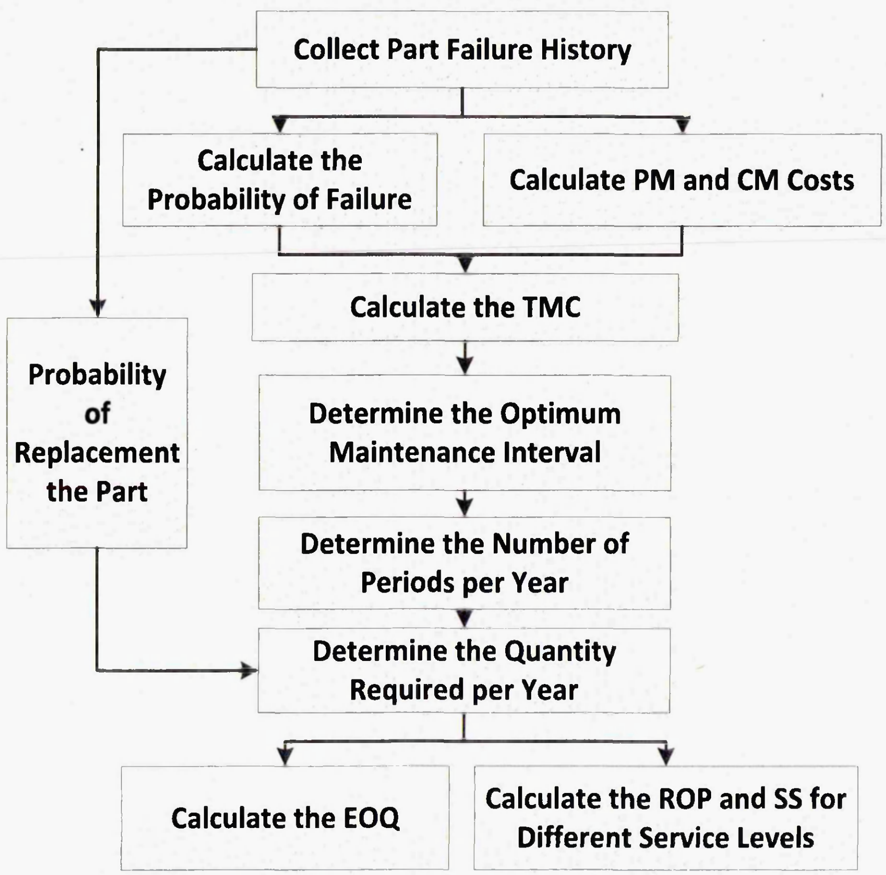


Figure 6-2: Description of Maintenance and Inventory Integrated Approach

Applying the proposed mathematical model, which considers the associated costs of both corrective and preventive activities as well as the probability of the failure to calculate the optimum time interval for each component at which the preventive maintenance should be carried out, preventive maintenance interval is optimised as extensively explained in chapter Five.

Once the Total Maintenance Cost (TMC) is applied and the optimum time to perform preventive maintenance for equipment is obtained, then this interval time is used as the lead time in order to find the economic order quantity (EOQ) (Equation 6-1).

$$\mathrm{EOQ} = \sqrt{\frac{2\mathrm{DOc}}{\mathrm{Hc}}} \qquad 6\text{-}1$$

Where:-

D Annual demand.

Oc Order cost for each order.

Hc Holding cost for each item per year.

Different assumptions that translate the actual real scenarios to calculate the reordering point (ROP) were suggested in the literature review. These assumptions lead to the fact that there are different equations applied to different assumptions.

Three probability models are suggested by Heizer and Rander (2014). The assumption of inconsistent demand is not applicable in this case, as the maintenance demand is assumed to be optimised and the demand should be stable. This results in two applicable assumptions to calculate ROP of which the first is :- constant demand and constant lead time (equation 6-2):-

$$ROP = D \times L + SS \qquad 6\text{-}2$$

Where:-

ROP Reorder Point

D Demand.

L Lead time.

SS Safety stock which can be considered as the spare parts required for one service (Heizer and Rander 2014).

The second assumption is: - constant demand and variable lead time (equation 6-3).

$$\text{ROP} = D_p \times \text{L}_p + \text{SS} \tag{6-3}$$

Where:

D_p Demand per period.

L_p Average lead time in period.

In this case SS is calculated by applying equation (6-4).

$$\text{SS} = (\text{Z} \times D_p \times \alpha_{Lt}) \tag{6-4}$$

Where:-

Z Service level (Heizer and Render 2014),

α_{Lt} Standard deviation of lead time in periods.

6.3 The Applications of the Proposed Integrated Approach

The proposed integrated approach is applied on the Ruston TA Turbine (seven equipment acting as a unit) within the oil and gas sector for validation purposes. Five of the seven turbines have to be in full working order to comply with the field requirement. From the history data, there were few occasions where the seven turbines were required to be online to fulfil the company's requirements. The company pursues a maximum and minimum policy for spare part inventory, with the minimum level taken as the reordering point. The order level is the quantity which will return inventory to the maximum level. One of the company administration inventory policies is to receive ordered inventory every 40 weeks.

The company's current inventory policy in place at the inventory department in regards to the cost of storage and the ordering cost is to add 10% to the purchase price of each item, with 2% and 8% representing the storage cost and ordering cost respectively. Two parts selected are for the minor services while three parts are selected for the major services.

6.3.1 Calculation of the Optimum Maintenance Interval

The proposed mathematical model extensively explained in Chapter Five is applied to calculate the optimum maintenance interval. The outcomes from the model shows that the optimum maintenance interval for a minor service should be performed at every 1,848hrs (11 weeks) and 7,560 hrs for a major service (45 weeks). However, the maintenance interval for major service is pushed backward to week 44 (7,392hrs) instead of week 45 in order to carry out the fourth minor service simultaneously with the major service to utilize all resources and minimise the disruption to the operations.

6.3.1.1 Maintenance's Demand for Spare Parts

In this section, the demand for the needed parts is calculated based on the schedule of the both minor and major services produced by the mathematical maintenance model. The probability of replacement (P_{rp}) of the parts is considered in this calculation. The percentages ofP_{rp} are estimated from the logbook of maintenance and movement of part within the inventory department (set on the basis of presumed required number by the maintenance and the actual usage of the spare parts).

Table (6-1) shows the probability of replacement for the selected parts and the required annual demand for each part which is calculated by multiplying the quantity per period by the number of periods a year. The quantity per period and the frequency of performing annual overhaul are determined by maintenance department. Part 3 and part 4 are estimated to have 50% and 60% probability of replacement respectfully and these values are observed from the estimated annual demand of maintenance department and the actual request from the inventory department.

For instance, the demand for part (1) from the maintenance department is four for each of the seven machines and the maintenance will be performed 4 times a year resulting in 112 parts needed annually.

Two spare parts are required of part (2) for each of the seven machines to be used during the four minor services, and the annual demand is calculated to be 56.Parts (3) and (4) have probability of replacement of (50% and 60%) respectively and accordingly the actual maintenance demand is 4 parts each. 7 parts are required from the maintenance for part (5) annually.

Table 6-1: Maintenance Annual Demand for Spare Parts

Part No	P_{rp} %	Demand per Service	Number of Planned Service	Number of Machines	Annual Demand
Part 1	100	4	4	7	112
Part 2	100	2	4	7	56
Part 3	50	1	1	7	4
Part 4	60	1	1	7	4
Part 5	100	1	1	7	7

6.3.2 Calculation of EOQ for Required Parts for Minor and Major Service

The next step is to determine the EOQ and reordering point (ROP) for spare parts involved in both minor and major services. The demand per period is obtained based on the assumption of stable demand (maintenance requirements are known and constant in terms of quantity for each period). By determining the number of periods in a year and the annual demand is then calculated by multiplying quantity per period by number of periods.

Table (6-2) presents the spare parts required for the services. The selected spare parts are classified as class (A) according to ABC classification.

Parts (1) and (2) are required for the minor service and parts (4), (5) and (6) are required for the major service. The parts quantity (QTY), maximum (MAX) and minimum (MIN) current policy are listed for comparison with the results of the integrated approach.

Table 6-2: Spare Parts Minor/Major Maintenance Services

Part No	Class	Description	Unit cost $	QTY	MAX	MIN
Part 1	A	Filter element	264.42	4	300	150
Part 2	A	Cleaning agent	23.64	2	120	60
Part 3	A	Igniter plug	812.18	1	16	8
Part 4	A	Fuel pump	2173.97	1	14	7
Part 5	A	Filter lube element	470.37	1	18	9

To determine the EOQ and ROP for spare parts for both services (minor and major), determining the number of periods in a year is required. The mean time between maintenance is obtained for the minor services (11 weeks) and maintenance is conducted 4 times a year. The major service of maintenance is conducted every 44 weeks, once a year.

Table (6-3) shows the annual demand for the spare parts, taking into account four periods for parts (1) and (2), and one period for the rest of the spare parts as they are just needed for the major service, which occurs once a year. Equation (6-1) is applied to obtain EOQ, considering the annual demand of parts (1 to 5), unite cost, holding cost (Hc) and ordering cost (Oc).

Table 6-3: Calculation of EOQ for Minor/Major Services

Part No	Annual Demand	Unit Cost	Hc 2%	Oc 8%	EOQ
Part 1	112	264.42	5.2884	21.1536	30
Part 2	56	23.64	0.4728	1.8912	21
Part 3	4	812.18	16.2436	64.9744	6
Part 4	4	2173.97	43.4794	173.9176	6
Part 5	7	470.37	9.4074	37.6296	7

6.3.3 Determining the Reordering Point (ROP) and Safety Stock (SS)

In this section, the two following two assumptions are applied to the case study:-

1. Both lead time and demand are constant.
2. The lead time is variable and the demand is constant.

6.3.3.1 Constant Lead Time (L) and Constant Demand (D)

In this section, the assumption is that the lead time and the demand are constant. Part (1) is taken as a case study from the minor services and part (3) from the major services. Equation (6-2) is applied to calculate the ROP.

6.3.3.1.1 Part (1) Minor Service

The lead time is the time of the optimum maintenance interval which is calculated in (chapter 5) and found to be around 11 weeks (77 days). The annual demand for part (1) is 112 spare parts used four times in a year. Thus, the safety stock is considered to be the spare parts needed for one minor service (28).

Equation (6-2) is applied and values are substituted as followed:-

$$ROP = \left(\left(\frac{112}{365}\right) \times 77\right) + 28 = 52\, parts$$

Table (6-4) captures the movement of part (1), which starts with ordering 30 of this part (1) to follow the economic order quantity calculated in table 6-3 The balance on hand is assumed to be the reordering point which is 52 and the lead time is MTBM.

Table 6-4: Movement of Part (1) Constant L and D

Lead time (weeks)	Order	Receive	Issue	Balance on hand
0	30			52
11		30	28	54
22	30		28	26
33	30	30	28	28
44	30	30	28	30
55	30	30	28	32
66	30	30	28	34
77	30	30	28	36
88	30	30	28	38
99	30	30	28	40
110	30	30	28	42
121	30	30	28	44
132	30	30	28	46
143	30	30	28	48
154	30	30	28	50
165	30	30	28	52

Figure (6-3) demonstrates the expected movement of part (1) for almost 17 years and illustrates a smooth movement avoiding any erratic movement or shortages at time of planned maintenance (Appendix D).

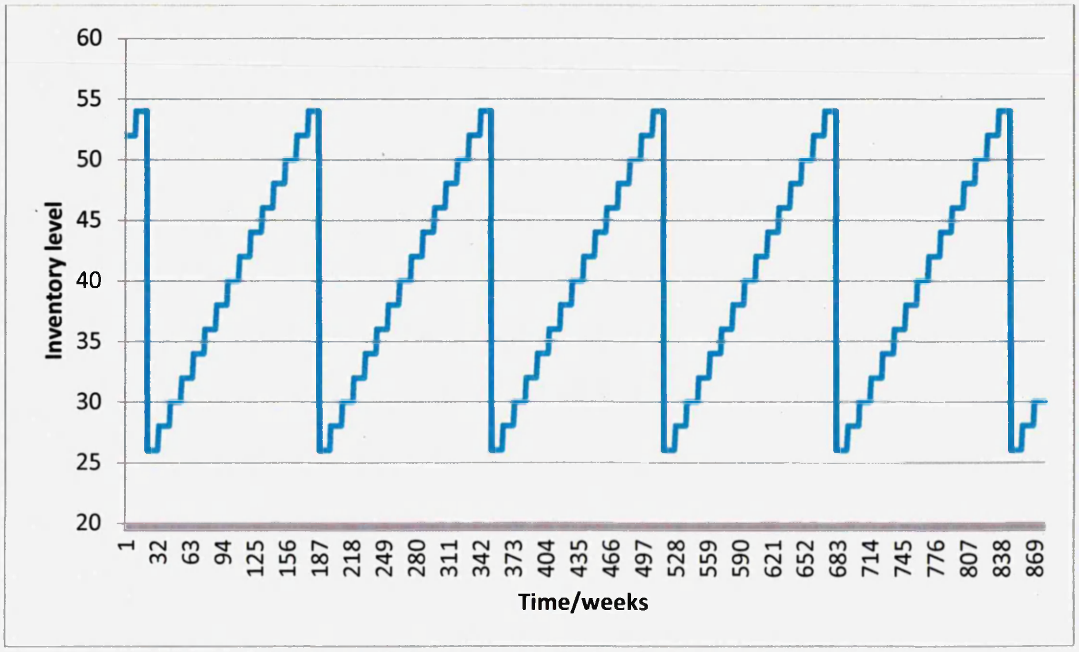


Figure 6-3: Part (1) Movement under Integrated Approach

6.3.3.1.2 Part (3) Major Service

The same process is applied to part (3) of which the annual demand is provided by the maintenance team to be 4 parts a year and the safety stock is 4 spare parts as required for one major service: $ROP = \left(\left(\frac{4}{365}\right) \times 308\right) + 4 = 8$

Figure (6-4) shows the movement of part (4) over almost 17 years. The EOQ is 6 parts for each order as obtained from table (6-3) and the lead time is equal to the maintenance interval of 44 weeks (308 days).

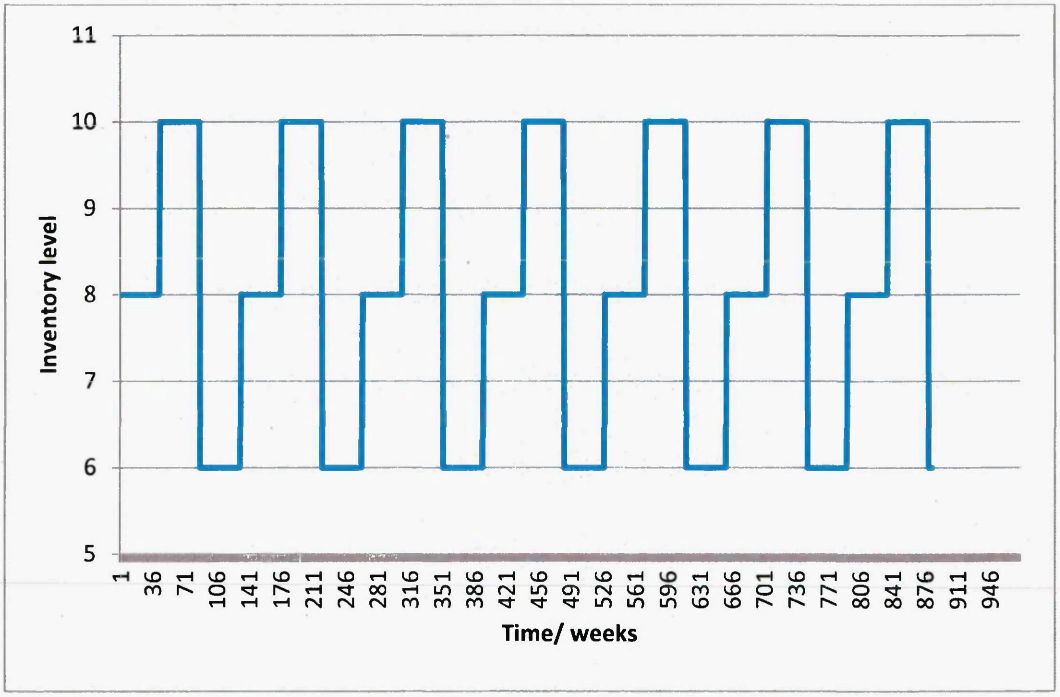


Figure 6-4: Part (3) Inventory Level Movement under Integrated Approach

6.3.3.2 Constant Demand and Variable Lead Time

In this section, reordering point ROP is calculated with the condition that the lead time is variable. The benefit of applying this condition so that the safety stock can be calculated at different service levels. Once the reordering point is calculated for different services levels, we assume that the receiving is every 40 weeks (the longest of lead time) to compare it with the current MIN/MAX policy.

The data recorded from the movement of the parts required for minor and major services show the variability of the lead time resulting into average of 234.444 days. The average lead time is than divided by the time between maintenance for minor services to calculate the average of lead time per day per period leading to average lead time in period and standard deviation of 3.044733045 and 0.45506052 respectively for minor services. The average lead time is divided by the major the time between maintenance for major services (308 days), resulting into the average lead time in period (0.761183261) and standard deviation (0.11376513) for the major services.

6.3.3.2.1 Calculation of ROP for Minor and Major Required Spare Parts

Table (6-5) presents the ROP and safety stock (SS) for the spare parts required to perform the minor services at service level 90%. The following example of calculating ROP (equation 6-3) for part (1) is provided to demonstrate the applied steps.

$$ROP = Demand\ per\ period \times Average\ lead\ time\ for\ minor\ services + safety\ stock$$

$$\mathrm{ROP} = 28 \times 3.044733045 + \text{saftey stock}$$

$$= 85.252 + \text{safety stock}$$

Equation (6-4) is applied to calculate the safety stock (SS) required for service level 90%. Z=1.28.

$$SS = 1.28 \times 28 \times 0.45506052 = 16$$

$$ROP = 85.252 + 16 = 102$$

In order to validate the accuracy of the use of periodic demand to calculate the ROP, the calculations are also made for the annual demand with the longest lead time (40 weeks) to reordering point annually. The reason for the use of the longest lead time is to simulate the worst case scenario.

$$\text{ROP} = \text{daily demand} \times \text{the longest lead time} + \text{safety stock}$$

$$= \left(\left(\frac{112}{365}\right) \times 280\right) + 16 = 102$$

Table 6-5: ROP and SS for Spare Parts (1) And (2) With SL 90%

Minor service parts		Service level 90% Z= 1.28	
Part No	Demand per period	Safety stock	ROP
Part 1	28	16	102
Part 2	14	8	50

Table (6-6) demonstrates ROP and SS for the spare parts required for the minor services with service levels (SL) 95% and 99.99%. It is obvious that the higher the service level is the greater the number of safety stock.

Table 6-6: ROP and SS for Spare Parts (1) And (2) With SL (95% and 99.99%)

Part No	Demand per Period	SL 95%, Z= 1.65		SL 99.99%, Z= 3.99	
		SS	ROP	SS	ROP
Part 1	28	21	106	51	136
Part 2	14	10	53	25	68

Table (6-7) demonstrates the demand per period (Dp) for the parts required for the major services (3, 4, and 5), the reorder point ROP and the safety stock SS at different service levels (SL). It is noted that the safety stock increases with the increasing of the required services level. Whenever the safety stock is calculated to be less than one the recorded value is to be rounded up to one. The average lead time in period (0.761183261) and standard deviation (0.11376513) is substituted in equation (6-4).

Table 6-7: ROP and SS for Spare Parts Used in Major Service

Part No	Dp	SL 90% Z= 1.28		SL95% Z= 1.65		SL 99.99% Z= 3.99	
		SS	ROP	SS	ROP	SS	ROP
Part 3	4	1	4	1	4	2	5
Part 4	4	1	4	1	4	2	5
Part 5	7	1	6	1	7	3	9

6.3.4 Application of the Integrated Approach with Restricted Lead Time Policy

In this section, the current inventory policy (maximum (MAX) and minimum (MIN) policy) is demonstrated for some of the spare parts and compared to the integrated approach with the company's conditions under the restricted receiving time. The expected number of orders placed (N) and the expected time between orders (T) are calculated using equation (6-5) and equation (6-6) respectively (Heizer and Rander 2014).

$$N = \frac{Annual\ Demand}{EOQ} \qquad \text{6-5}$$

$$T = \frac{Number\ of\ working\ days}{N} \qquad \text{6-6}$$

The number of working days is assumed to be 365 days. Table (6-8) demonstrates the number of orders and the time between orders for the spare parts for both minor and major services. The annual demand of part (1) is 112 and EOQ = 30 resulting to ($N = 4\ and\ T = 13$). The ROP and EOQ for part (2) are 56 and 21 respectively leading to $N = 3\ and\ T = 17$. For parts (3, 4 and 5) the number of orders is calculated to be one and the time between orders is calculated to be 52 weeks. However, it is considered to be 40 weeks because the company receives spare parts in 40 weeks instead of 52 weeks.

Table 6-8: Number of Orders N and Time between Orders T

Part No	N	T (weeks)
Part 1	4	13
Part 2	3	17
Part 3	1	40
Part 4	1	40
Part 5	1	40

6.3.4.1 Part (1) Filter Element (Minor Service)

Table (6-9) shows the historical movement of part (1) and demonstrates the shortage occurs in week 90 in the second year which was (-8), despite the fact that the annual average of filters in the stock is higher in comparison with average annual inventory with service levels at 90%, 95% and 99%. That resulted from applying the integrated approach (see Table 6-10). This can be attributed to the number of maintenance that occurred in the second year, which is more than the first year and because of the prolonged of the lead time.

Table 6-9: Part (1) Movement under the Current MAX/MIN Policy

Week	Order	Receive	Issue	Balance O/H
0	150			150
9			28	122
18			28	94
27			28	66
36			28	38
40		150		188
45			28	160
Inventory average				116.9
53				160
54	150		28	132
58			28	104
63			28	76
72			28	48
81			28	20
90			28	-8
94		150		142
99			28	114
Inventory average				87.5

Table (6-10) illustrates a significant reduction in the inventory level and a smoother movement of the spare parts. Reordering point for part (1) is calculated and added to the safety stock quantity which resulted differently at different service level.

A small shortage is predicted to occur a few times towards the end of the second year at 90% SL, which can be avoided by increasing the annual demand or by increasing the order for the second year. No shortage in parts is predicted to occur at service levels 95% and 99.99%, which can be the solution as well to avoiding the shortage with SL 90%.

Table 6-10: Movement of Part 1 under Different Service Levels

$N = 4,\ T = 13$				SL 90% SS =16	SL 95% SS =21	SL 99.99% SS = 51
Weeks	Order	Receive	Issue	On Hand	On Hand	On Hand
0	30			102	106	136
11			28	74	78	108
13	30			74	78	108
22			28	46	50	80
26	30			46	50	80
33			28	18	22	52
39	30			18	22	52
40		30		48	52	82
44			28	20	24	54
52	30					
Average inventory first year				49.5	53.5	83.5
53		30		50	54	84
55			28	22	26	56
65	30			22	26	56
66		30		52	56	86
66			28	24	28	58
77			28	-4	0	30
78	30			-4	0	30
79		30		26	30	60
88			28	-2	2	32
91	30			-2	2	32
92		30		28	32	62
99			28	0	4	34
Average inventory second year				20.6	21.8	51.8

6.3.4.2 Part (2) Cleaning Agent (Minor Service)

Table (6-11) demonstrates the movement of part (2) under the current policy (MAX/MIN) and at week 81, the maintenance faced shortage of spare parts leading to interrupting the operations of maintenance. The average inventory level of part (2) for the first year is 39.14 and 36.28 for the second year.

Table 6-11: Part (2) Movement under the Current MAX/MIN Policy

Weeks	Order	Receive	Issue	Balance on hand
0	60			60
9			14	46
18			14	32
27			14	18
36			14	4
40		60		64
45	60		14	50
45				50
54			14	36
63			14	22
72			14	8
81			14	-6
85	60	60		68
90			14	54
99			14	40

Figure (6-5) captures the movement of part (2) under the current policy (MIN/MAX). It is obvious that the level of inventory of the part is erratic and result in 6 parts shortages in week 81.

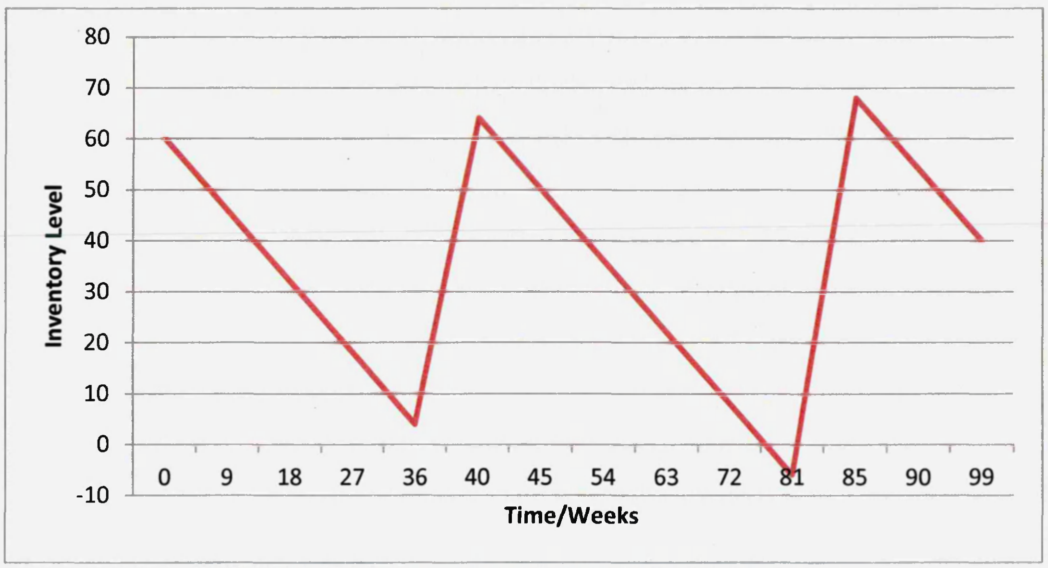


Figure 6-5: Movement of Part (2) MIN/MAX Policy

Table (6-12) demonstrates the three service levels 90%, 95% and 99.99% for part (2). No shortages are recorded in inventory and the average inventory level at SL 90% and 95 % is less than the average inventory level of the current MIN/MAX policy.

Table 6-12: Part (2) Inventory Movement under Different Service Levels

$N = 3, T = 17\ Weeks$				SL 90% SS=8	SL 95% SS=11	SL 99.99% SS = 25
Weeks	Order	Receive	Issue	On hand	On hand	On hand
0	21			51	53	68
11			14	37	39	54
17	21			37	39	54
22			14	23	25	40
33			14	9	11	26
34	21			9	11	26
40		21		30	32	47
44			14	16	18	33
Average first Year				26.5	28.5	43.5
55			14	2	4	19
57		21		23	25	40
66			14	9	11	26
68	21			9	11	26
74		21		30	32	47
77			14	16	18	33
79		21		37	39	54
85	21			37	39	54
91		21		58	60	75
99			14	44	46	61
Average Inventory second year				27.45	29.45	44.45

6.3.4.3 Part (3) Plug igniter (Major Service)

Table (6-13) presents the movement of part (3). No shortages in part (3) were recorded under the current MAX/MIN policy. The average of inventory level is 8 and10 parts respectively for two years.

Table 6-13: Part (3) Movement under Current MAX/MIN Policy

Weeks	Order	Received	Issue	Balance on hold
0	8			8
36			4	4
40		8		12
Average first year				8
53				12
72			4	8
72	8			8
104				8
Average second year				10

Table (6-14) shows the inventory level of part (3) at SL 90%, 95% and 99.99%. The average annual inventory were decrease when applying the proposed integrated approach in comparison to the movement of the part under MAX/MIN policy.

Table 6-14: Part (3) Movement under Different Service Levels

$N = 1, T = 40$				SL90% SS=1	SL95% SS=1	SL 99.99% SS = 2
Weeks	Order	Receive	Issue	On hand	On hand	On hand
0	6			4	4	5
40		6		10	10	11
44			4	6	6	7
Average first year				7	7	8
53				6	6	7
88			4	2	2	3
88	6			2	2	3
Average second year				3	3	4
104				2	2	3
128		6		8	8	9
132			4	4	4	5
132	6					
Average third year				5	5	6

6.3.4.4 Part (4) Pump Fuel (Major Service)

Table (6-15) demonstrates the movement of part (4) under MIN/MAX policy and it shows no shortages in inventory of part (4) for three years.

Table 6-15: Part (4) Movement under Current MAX/MIN Policy

Weeks	Order	Received	Issue	Balance on Hand
0	7			7
36			4	3
40		7		10
Average first year				7
53				10
72			4	6
72	7			6
Average second year				7
108			4	2
112		7		9
144			4	5
144	7			
Average third year				6

Table (6-16) presents the inventory movement of part (4) under the proposed integrated approach and it shows that average inventory with SL 90% and 95% is less than the average of inventory in the case of MAX/MIN policy.

Table 6-16: Part (4) Movement under Different Service Levels

$N = 1, T = 40$				SL90% SS=1	SL 95% SS=1	SL 99.99%, SS = 2
weeks	order	receive	issue	on hand	on hand	on hand
0	6			4	4	5
40		6		10	10	11
44			4	6	6	7
Average first year				7	7	8
53				6	6	7
88			4	2	2	3
88	6			2	2	3
Average second year				3	3	4
104				2	2	3
128		6		8	8	9
132			4	4	4	5
132	6			4	4	5
Average third year				5	5	6

6.3.4.5 Part (5) Element Filter Lubol (Major Service)

Figure (6-6) demonstrates the inventory level for part (5) over three years and its erratic movement and shortage of parts clearly happening and will delay performing the maintenance on time.

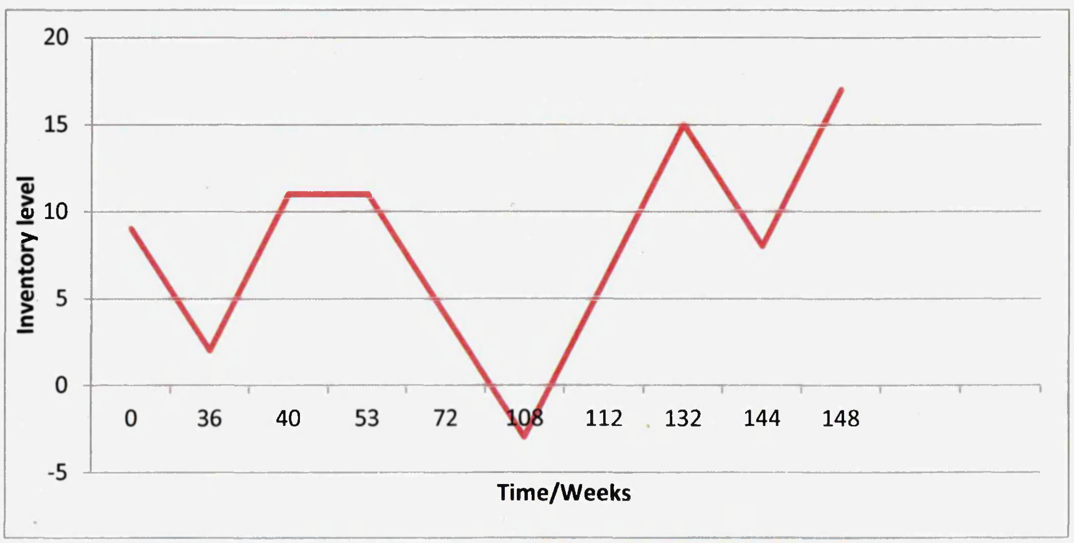


Figure 6-6: Inventory Level of Part (5) (MIN/MAX Policy)

Table (6-17) shows the movement of part (5) under the policy selected by the company, which is the MAX/MIN policy. Shortage was recorded for this part during week (108).

Table 6-17: Part (5) Movement under Current MAX/MIN Policy

Weeks	Order	Received	Issue	balance on hand
0	9			9
36			7	2
40		9		11
Average inventory first year				7
53				11
72			7	4
72	9			4
Average inventory second year				8
108			7	-3
108	9			0
112		9		6
132		9		15
144			7	8
148		9		17
Average inventory third year				12

Table (6-18) demonstrates the application of the integrated approach under three service levels (90%, 95% and 99.99%) for three years with no shortages occur for the maintenance demand.

Table 6-18: Movement of Part (5) Under Different Service Level

N = 7 / 7 =1 T = 365/1 = 365 days				SL 90%SS=1	SL95% SS=1	SL 99.99% SS = 3
weeks	Order	Receive	Issue	On hand	On hand	On hand
0	7			6	7	9
40		7		13	14	16
44			7	6	7	9
44	7					
Average first year				8	9	11
84		7		13	14	16
88			7	6	7	9
88	7					
Average second year				8	9	11
128		7		13	14	16
132			7	6	7	9
132	7					
Average third year				8	9	11

Figure (6-7) demonstrates the inventory level of part (5) and its movement for three years. No shortage in demand is predicted and generally, the movement of the part is not erratic.

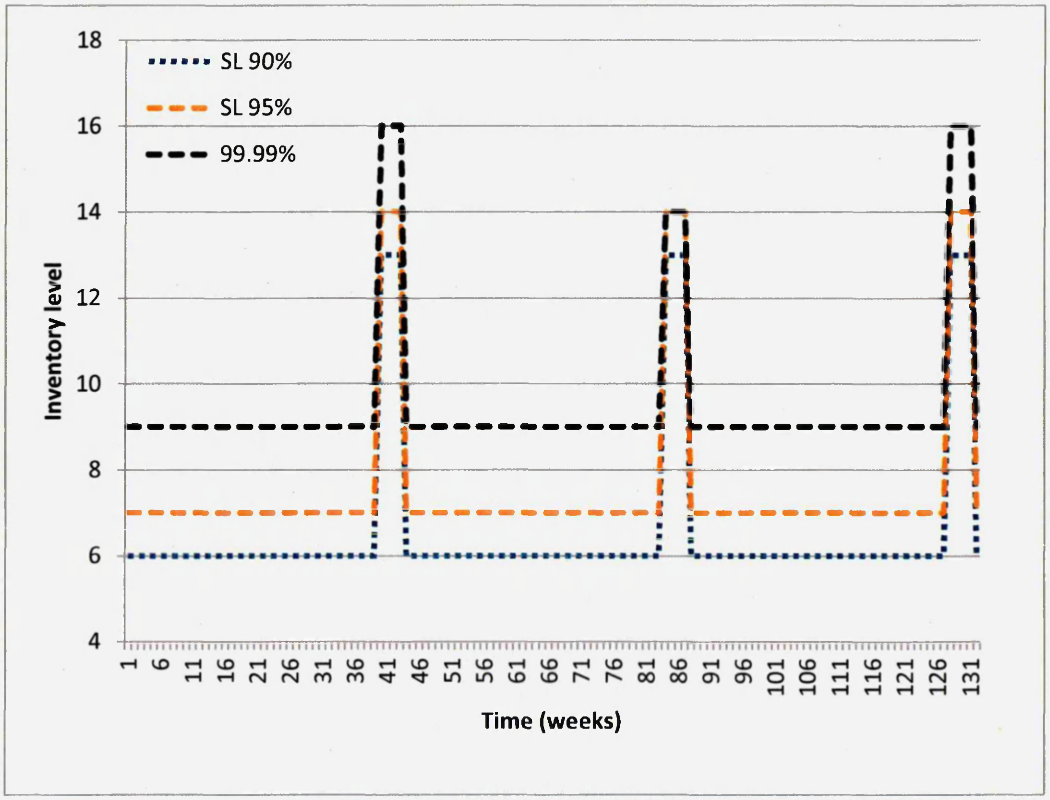


Figure 6-7: Inventory Level of Part (5) with SL (90%, 95% and 99.99%)

6.3.5 Comparison of inventory Level and Movement of Part (1) Under Different Inventory Policies

In this section, a comparison for part (1) movement is conducted to understand the impact of the integrated approach. The comparison is set to compare between the movement of part (1) under three situations:-

- MAX/MIN policy which is the current inventory policy for the case study.
- The application of the integrated approach with the variable lead time.
- The application of the integrated approach in an optimum condition.

Figure (6-8) presents the movement of part (1) within two years under MAX/MIN inventory policy. The inventory department faced a difficulty of supplying the maintenance demand and shortages occurred towards the end of the second year.

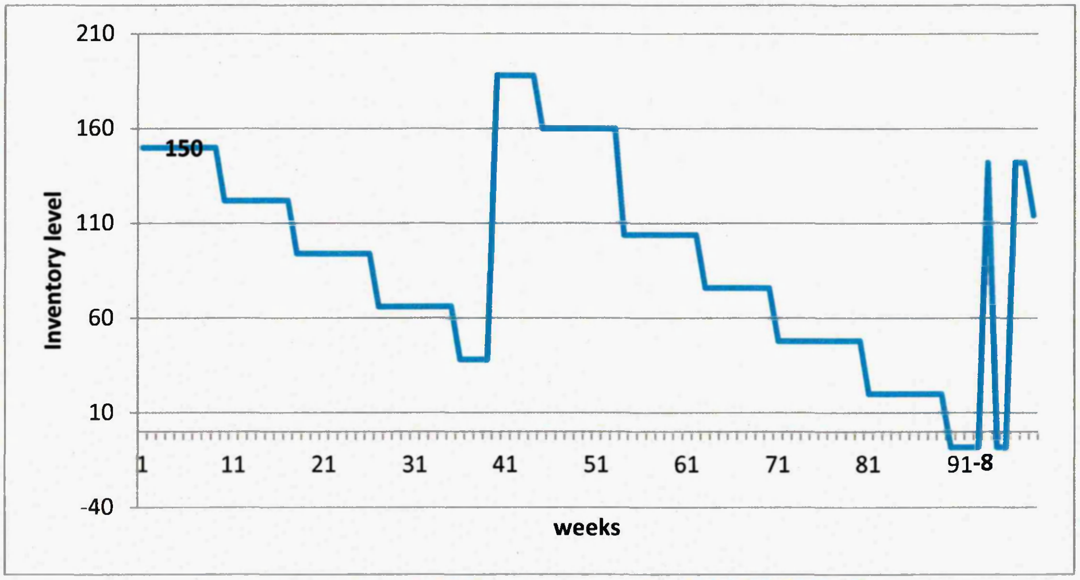


Figure 6-8: Part (1) Movement under MAX/MIN Policy

Figure (6-9) shows the movement of the part (1) for eight years under the proposed integrated inventory policy with conditions of restricted lead time.

It is obvious that the inventory level drops down gradually as the service levels reduced from 99.9% to 90%. Part (1) experiences shortage in supplying the maintenance's demand on week 77 under SL 90%, whereas the first shortage of part (1) occurs at week 143 with SL 95%. Under the service level 99.99, the supply of part (1) required for maintenance interval is provided without shortage until week 221. Because of advised prolonged lead time by the company the part movement deceases with the time and the recovery of the inventory level seems to be impossible.

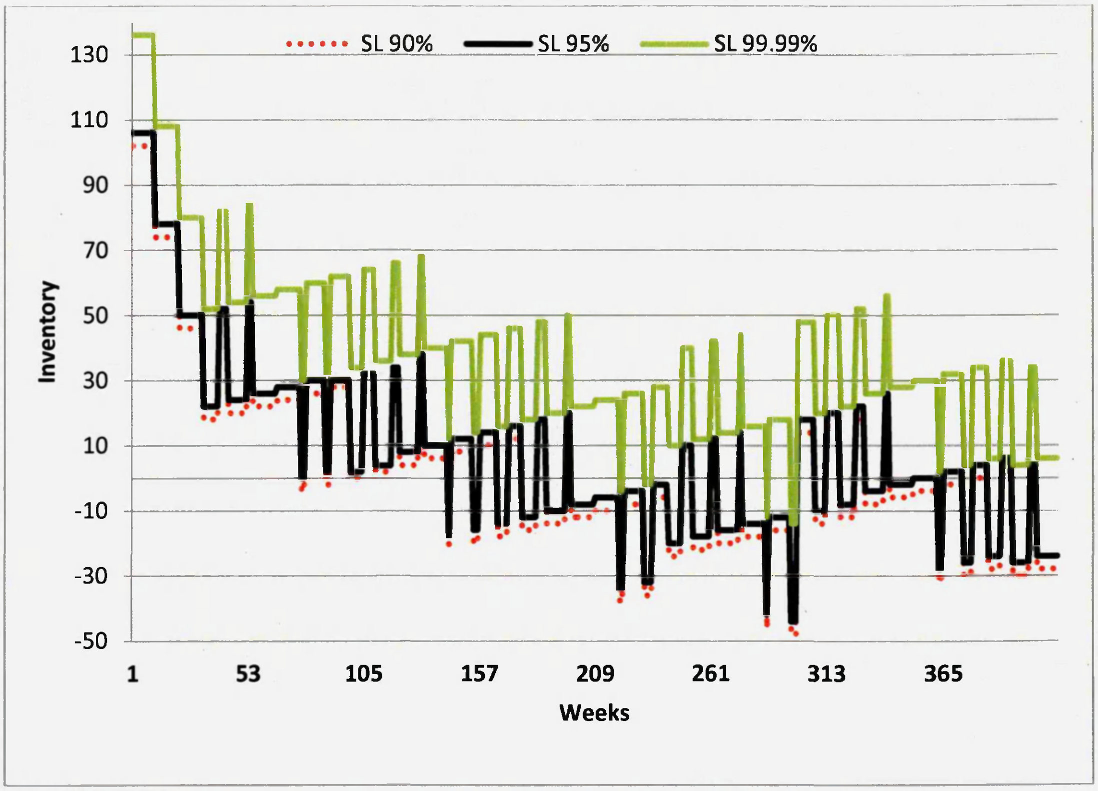


Figure 6-9: Movement of Spare Part (1) with Different SL for 8 Years

In comparison with figure (6-3) which demonstrates the expected movement of part (1) under the integrated policy with the lead time is equal to the time between maintenance intervals for almost 17 years. It illustrates a smooth movement avoiding any erratic movement or shortages in time of planned maintenance.

Figure (6-10) shows the annual average inventory of part (1) for 17 years. The calculations show that the highest annual average occurs at year 13 with 49.4 and the least average occurs at year 11 with 32.1 parts. In contrast, the current inventory policy MIN/MAX showed that the average inventory for part (1) was 116.9 and 78.5 for two years respectively. Whereas the results of applying the integrated model on the selected company (case study) which required variable lead time showed improvement in comparison with MIN/MAX policy. However, because of the lengthy of the lead time suggested by the company, shortages would occur as shown for some parts over the years especially with low service level (90%). The author would advise the company to avoid the shortage of the parts by follow these steps:-

- Increase service level in order to insure no shortage occurs.
- Select the suitable order quantity which meet the expected inventory level that covers the services in the future.

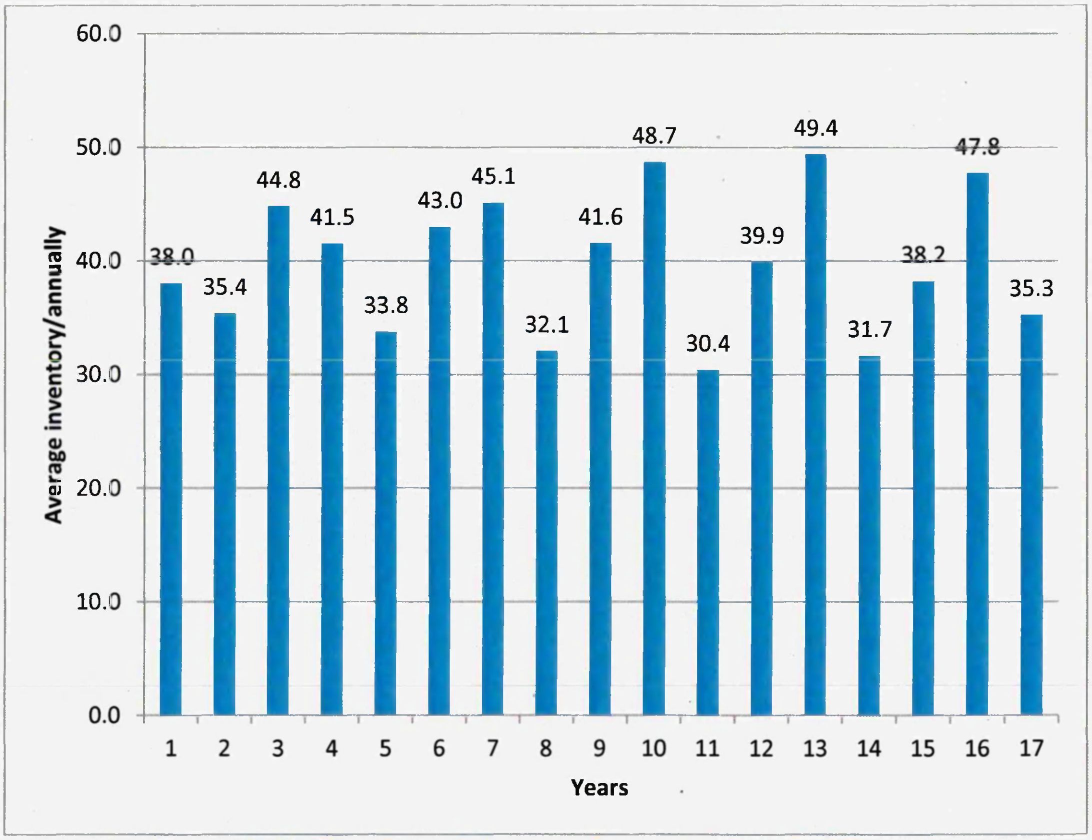


Figure 6-10: The Annual Average Inventory Level of Part (1)

6.3.6 Comparison of the Cost Effectiveness of Inventory Policies

To calculate the effectiveness of the proposed integrated model, the average of annual balance on hand inventory of MAX/MIN policy is compared against the proposed approach with its different service levels.

Table (6-19) demonstrates the used spare parts for two years and their costs. The parts, item cost, average balance on hand and the total cost of each of the spare parts is provided for two years under the MAX/MIN policy.

Table 6-19: Total Parts Cost for Year 1 and 2 under MAX/MIN Policy

First year			
Part NO	Item cost ($)	average balance on hand	Total cost ($)
Part 1	264.42	116.9	30910.698
Part 2	23.64	39.14	925.2696
Part 3	812.18	8	6497.44
Part 4	2173.97	7	15217.79
Part 5	470.37	7	3292.59
Overall total parts cost in year 1			$56843.7876
Second year			
Part 1	264.42	87.5	23136.75
Part 2	23.64	36.28	857.6592
Part 3	812.18	10	8121.8
Part 4	2173.97	7	15217.79
Part 5	470.37	8	3762.96
Overall total parts cost in year 2			$ 51096.96

Figure (6-11) presents the average cost of the spare parts under the MIN/MAX policy for year one ($56843.7876) and Year two ($51096.9592). It is notable that, the shortages in parts mostly occurred within the second year under the MIN/MAX inventory policy, which can be attributed to the lengthy of the lead time to deliver once the request of spare part is established.

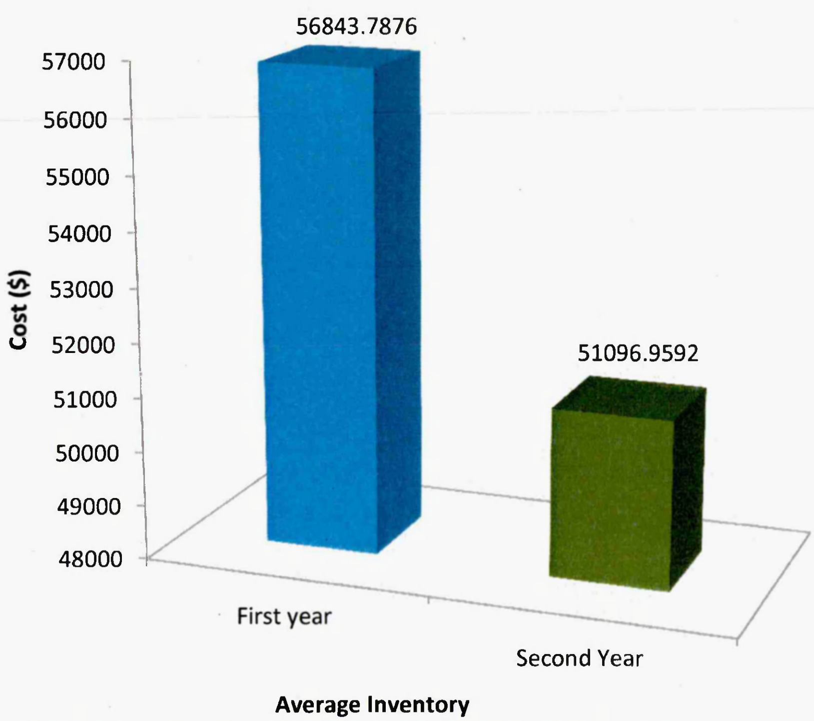


Figure 6-11: Average Inventory Cost of Spare Part under MIN/MAX Policy

Most of the shortages occurred for the spare parts that involved in the minor service. The reason of the shortages is attributed to the frequency of carrying the minor services within the leap of one receiving order. For instance, the frequency of the preventive maintenance activities is assumed to be conducted every 9 weeks following the manufacturer recommendations. In the first year the spare parts were issued 5 times and in the second year the spare parts were issued 6 times which drops the overall inventory cost.

Table (6-20) illustrates the average balance on hand and the total cost of parts with the service levels 90%, 95% and 99.99% respectively. It is noticeable that the higher the service level the higher the total cost of spare parts which can be attributed to the increase of safety stock leading to the increase of the balance on hand.

Table 6-20: Total Parts Cost for Two Years with Different SL

First year				
Part No	Item cost ($)	average balance on hand		
		SL90%	SL95%	SL99.99%
Part 1	264.42	49.5	53.5	83.5
Part 2	23.64	26.5	28.5	43.5
Part 3	812.18	7	7	8
Part 4	2173.97	7	7	8
Part 5	470.37	8	9	11
Total parts cost		$38381.26	$39956.59	$52170.68
Second year				
Part 1	264.42	20.6	21.8	51.8
Part 2	23.64	27.45	29.45	44.45
Part 3	812.18	3	3	4
Part 4	2173.97	3	3	4
Part 5	470.37	8	9	11
Total parts cost		$18817.38	$19652.334	$31866.424

Figure (6-12) demonstrates the total cost of the inventory for year (1) and year (2) for the spare parts at different service level 90%, 95% and 99.99%. The difference in the total cost (for year 1 and year 2) within the same service level is attributed to the lengthy of the lead time and the frequency of issuing the spare parts. The balance on hand is assumed to start at the reordering point and because of the lengthy lead time, the level of inventory dose not recover back to the original level.

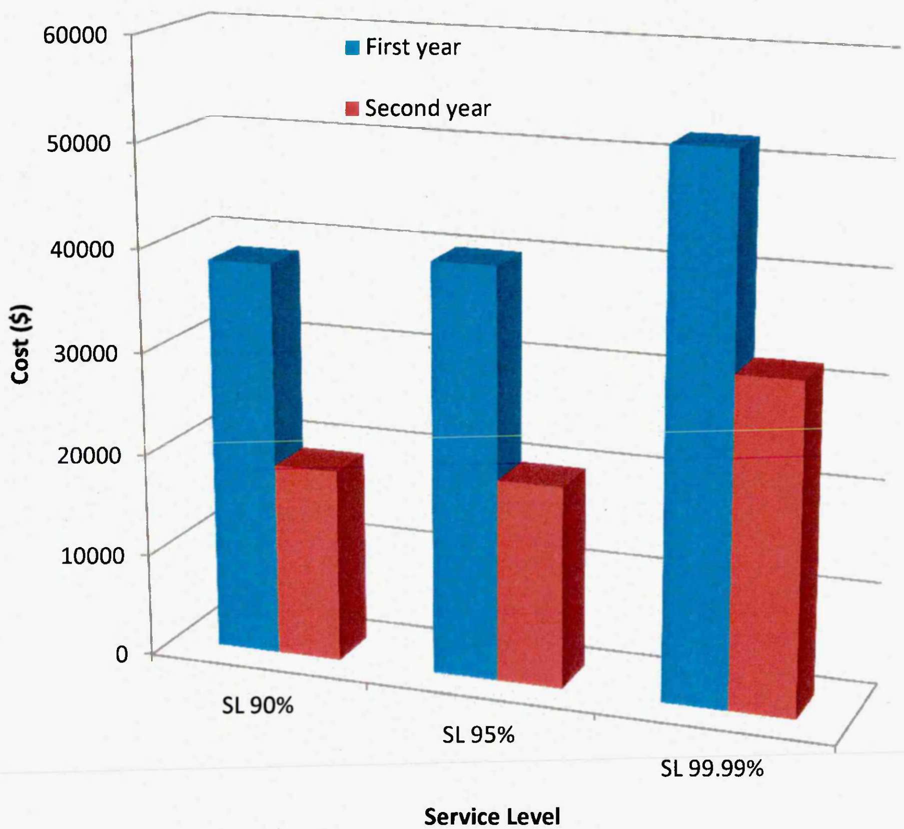


Figure 6-12: Parts Cost for Two Years with SL (90%, 95% and 99.99%)

In comparison between the average cost of the MIN/MAX policy and the proposed integrated approach, it is obvious that the highest cost of parts is associated with the MAX/MIN current policy. Whereas, the highest inventory cost recorded from applying the proposed approach occurs at 99.99% service level followed by 95% service level and the least inventory cost occurs at 95% this due to the level of safety stock required for each service level.

6.4 Conclusion

The availability of spare parts is imperative for the success of sustainable maintenance operations. The risk of shortages in supplying the maintenance department with the required spare parts on time could result in costly operation stoppages while overstocking can lead to additional inventory's costs. This chapter presented the proposed integrated approach between the optimised maintenance intervals and the inventory management of spare parts to minimise total inventory cost and provided answers to two most important questions, which are “How much to orders?” and “When to order?”.

The high cost of spare parts within the petroleum industry and the need for rapid responses due to high downtime costs and the risk of stock obsolescence drive the need to address this particular matter. The outputs of the model of optimising the maintenance interval processed to the inventory management for the spare parts to be ordered ensuring sufficient stock for regular maintenance to be performed. The calculated optimum maintenance intervals were used as a reference point to optimise the spare parts' EOQ and ROP. The applications of the proposed integrated approach achieve promising results that can be summarised as follows:-

- Reducing the holding cost of the spare parts.
- Smoothening the reordering cycle while guaranteeing the availability of spare parts at the required time needed by the maintenance department.
- Avoiding erratic movement of the spare parts.

- Providing the possibility of predictability of future movement of spare parts and allowing the treatment of any shortage expected by altering either the safety stock or the EOQ.
- Decreasing the overall cost of inventory by decreasing the total annual average of the spare parts.

Chapter Seven

Risk Assessment Model for the Petroleum Equipment

This chapter covers the risk assessment for equipment within the petroleum industry. A mathematical model is proposed to estimate the likelihood of risk (LOR) and advice the optimum time of inspection for machines and their parts within the industry. The impact of the consequences of the risk is evaluated for equipment within the petroleum industry and modified equations are proposed for system performance and financial loss. Applications are provided to demonstrate the validity of the proposed equations.

7.1 Introduction

As discussed in Chapter Five, the purpose of "operational maintenance level" is to plan and identify the most optimum maintenance intervals from the perspective of reliability, availability and cost reduction. However, unpredictability or uncertainty of the occurrence of the failure and its undesirable consequences demand more risk assessment and inspection for two main reasons:

1. To enhance the system's reliability in order to prevent the possibility of the occurrence of failure and eliminate the consequences of the risk by means of ensuring that the equipment would serve as attended or planned till the next maintenance interval.
2. To prioritise the job orders according to the overall risk evaluation.

In order to enhance the reliability of a system, inspection interval would be planned to ensure that the equipment's reliability would meet the expectation of the planned preventive maintenance. Inspection frequency is determined according to risk exposure, which can be used to avoid any unacceptable risk (Chang et al 2005).

To estimate the probability of the risk for equipment and to provide guidelines for the inspectors, a mathematical equation is developed. Four main areas are considered to evaluate the consequences of the risk which are "performance, financial, human and ecology loss". The proposed risk assessment model is applied on two case studies for the purpose of validation and the results show a promising improvement in estimating the likelihood of the risk and enhanced estimation for consequences. The rest of the chapter is organized mainly as:-

- Architecture of the proposed model
- The likelihood of risk and an explanation of derivation of the mathematical equation.
- Consequences of the failure and developed equations for evaluation of risk impact on the above mentioned four areas.
- Applications of the proposed model.

7.2 Architecture of the Proposed Model

In this chapter, incorporation of modified models and a newly developed equation is proposed in order to assess the risk. The proposed model is expected to enhance estimation of the risk and its consequences instead of the conventional method that considers the multiplication of the likelihood by consequences, which can be misleading. The proposed risk assessment model relies on the use of both qualitative and quantitative methods.

Figure (7-1) demonstrates the description of the proposed model of estimating the risk for equipment within the petroleum industry and the steps are illustrated as follows:-

7.2.1 Likelihood Assessment

In this step, an estimation of the probability of failure occurrence is performed by qualitative and quantitative means to build generic conception that consider the majority of the facilities within the petroleum industry.

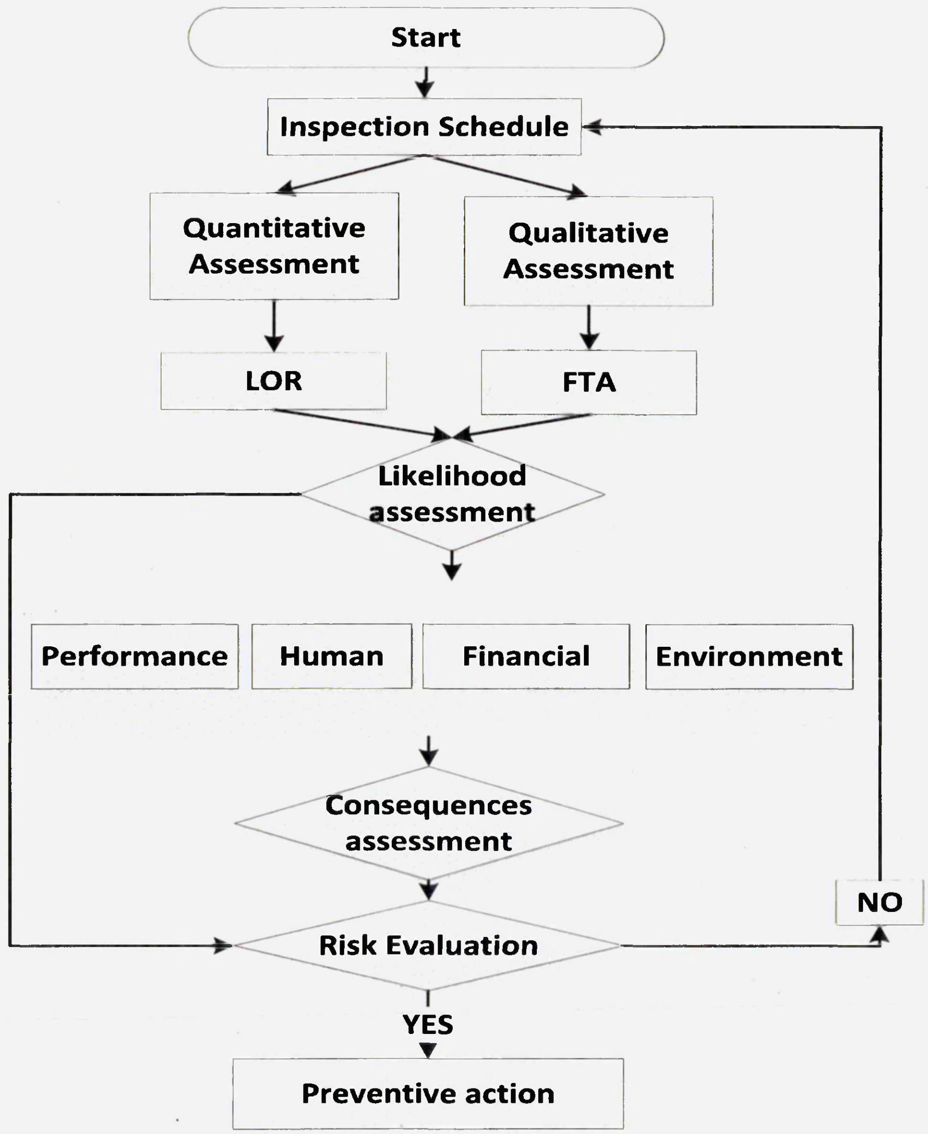


Figure 7-1: Description of Risk Estimation Model

7.2.1.1 Qualitative Assessment

Probabilistic failure analysis is conducted using the fault tree analysis (FTA). The use of FTA along with components' failure data and human reliability data, enables the determination of the frequency of occurrence of an accident. The top event is identified based on the detailed study of the process, control arrangement, and behaviour of components of the unit/plant. A logical dependency between the causes leading to the top event (failure) is developed in this stage.

7.2.1.2 Quantitative Assessment: Likelihood of Risk (LOR)

Quantitative analysis is conducted to estimate the probability of the occurrence of the risk. In order to validate the proposed risk estimation model, a degree of acceptance of risk has to be set up against the estimated risk. The developed proposed mathematical model (Likelihood of Risk (LOR)) is based on the assumption that the risk depends exponentially on time *P*, where *P* is the physical age of the equipment and *d* is the design age of part/machine.

The assumption is that risk depends exponentially on time *P* :

$Risk \propto P$

Where;-

P Physical age of equipment.

$$Risk(P) = F(\Delta P)\, G^{\frac{P}{d}} \tag{7-1}$$

Where, G is a positive growth factor of the risk and the time required for risk to increase by one factor of G. $F(\Delta P)$ is the probability of the failure of the part/machine.

$$Risk\ (P + d) = F(\Delta P)\, G^{\frac{P+d}{d}} \tag{7-2}$$

Where:-

d The designed life of equipment or parts.

$$Risk\ (P + d) = F(\Delta P)\, G^{\frac{P}{d}}\, G^{\frac{d}{d}} \tag{7-3}$$

Therefore, if d=0 and G>1 then LOR (P) has exponential growth. Thus formula (7-3) can be written mathematically as:-

$$LOR = F(\Delta P)\, e^{\frac{P}{d}} \qquad 7\text{-}4$$

Where:

LOR likelihood of risk, $F_{\Delta P}$ the probability of failure.

Bertolini et al (2009) proposed classification of the occurrence degree of the failure to be compared to the outcomes of probability of the failure ($F_{\Delta t}$) as shown in table (7-1). He relies on the Cumulative Weibull distribution model to generate $F_{\Delta t}$. However, in this work, the same classification is applied but will be allocated to LOR instead of using the $F_{\Delta t}$. For example, comparing the likelihood of the risk between two equipment at a particular point in time (*P*) would have to follow these steps:-

1. Calculating the likelihood of risk (LOR)
2. Comparing the outcomes of LOR for the equipment with the classification shown in table (7-1).

Table 7-1: Assigning Probability

Class	Key Word	Absolute value of $F_{\Delta t}$/LOR
A	Very Unlikely	0.001
B	Unlikely	0.05
C	Neutral	0.3
D	Likely	0.5
E	Very Likely	1

7.2.2 Consequences assessment

The objective of this phase is to estimate the consequences of failure and its contribution to the system to prioritize equipment and their components on the basis of their undesirable contribution to the system. Consequence analysis involves assessment of likely consequences in the case that a failure scenario does materialize. Khan and Haddara (2003) identified four impacted areas where consequences of the failure have to be evaluated which are: - System performance loss(A), financial Loss(B), human health loss(C) and environmental loss(D). Mathematical presentation and qualitative evaluation was provided by Khan and Haddara (2003) to calculate the damages in terms of failure and accordingly the prioritization of the equipment maintenance is advised. Equation (7-5) presents the combined loss in order to find the overall consequences of the risk (Khan and Haddara, 2003).

$$Consequences = \{ 0.25\, A^2 + 0.25\, B^2 + 0.25\, C^2 + 0.25\, D^2 \}^{0.5} \qquad 7\text{-}5$$

The shortcoming of applying this equation is that it may result in the same value with different scenarios. For example, with factor A =100 and factor B=50 would result into the same value when factor *A*=50 and factor *B*=100 if the other factors were neglected. The recommendations provided by the author in this case is to provide chance for the company practitioners to set the weight for each loss consequence that suit their companies environment, therefore, equation 7-5 can be modified to a more generic format as follows:

$$Consequences = \{ W_a\, A^2 + W_b\, B^2 + W_c\, C^2 + W_D\, D^2 \}^{0.5} \qquad 7\text{-}6$$

Where:-

W_a The weight of performance loss.

W_b The weight of financial loss.

W_c The weight of human health loss.

W_D The weight of environment loss.

The maintenance team has to prioritize the importance of the loss factors while investigating the four loss factors and for instance could first prioritize human health followed by environmental loss, financial loss and system performance and reflect that on the weights accordingly.

7.2.2.1 System Performance Loss (A)

Factor (A) represents the system performance loss due to the equipment failure. Equation (7-7) is developed to represents the system performance loss and it shows two possible scenarios:-

1. If the equipment has a stand-by redundancy then this factor is considered as zero.
2. If the equipment is a vital to the system then the proposed quantification scheme by Khan and Haddara (2003) is considered to take the measures of the loss as shown in table (7-2).

$$A = \begin{cases} Function\ performance & Table\ (7-2) \\ 0 & otherwise \end{cases} \qquad 7\text{-}7$$

Table 7-2: Performance Function (Khan and Haddara 2003)

Class	Description	Function (operation)
I	• Very important for system operation • Failure would cause system to stop functioning	8-10
II	• Important for good operation • Failure would cause impaired performance and adverse consequences	6-8
III	• Required for good operation • Failure may affect the performance and may lead to subsequent failure of the system	4-6
IV	• Optional for good performance • Failure may not affect the performance immediately but prolonged failure may cause system to fail	2-4
V	• Optional for operation • Failure may not affect the system's performance	0-2

7.2.2.2 Financial Loss

Loss factor (B) accounts for the damages to the property or/and equipment and major costs are involved as a consequence of the failure. Financial loss (B) is calculated by the developed equation (7-8).

$$B = ((B_p + C_{mc}) - P_{mc})/P_{mc} \quad 7\text{-}8$$

Where:

B_p Denotes financial loss of the property and the facilities in terms of explosion or fire.

C_{mc} Corrective maintenance cost.

P_{mc} Preventive maintenance cost.

Khan and Haddara (2003) proposed equation (7-9) to calculate the B_p as follows:-

$$B_p = (AR) \times (AD)/UFL \quad 7\text{-}9$$

Where:

AR Area under the damage radius (m^2)

AD Asset density in the vicinity of the event (up until 500 m radius) ($\$/m^2$)

UFL The level of an unacceptable financial loss which assumed by Khan and Haddara (2003) as 1000.

C_{mc} Costs incurred due to the failure and calculated by the developed equation (7-10) which has been extensively demonstrated in Chapter Five:-

$$C_{mc} = \left\{\left(\sum_{i=1}^{n} C_{sp_n} \times P_{rp_n}\right) + (t_{ti} + t_{su}) \times \frac{\alpha}{\pi} + (V \times C_{pd}) + L_C + C_{wd} + C_{sd} + \left(\frac{(t_{ti}+t_{su})}{\pi} \times C_{pd}\right) + (C_{MT} - D_{FT}) \times C_h + (X_1 \times t_{tc} \times S_{mh}) + (t_{ti} + t_{su}) \times S_{oh} \times X_2\right) \quad 7\text{-}10$$

Where: -

C_{sp} Cost of spare parts ($).

P_{rp_n} Probability of replacement (%).

t_{ti} Production time loss excluding machine setup time (hrs).

t_{su} Machine set up time (hrs).

α Department's income due to one barrel ($).

π Production cycle time (hrs).

V Number of damaged production by barrel.

C_{pd} Value of damaged production ($).

Lc Legal fines in case of environmental damages ($).

C_{wd} Cost of cleaning non-hazardous and hazardous materials ($).

C_{sd} Cost of damaged parts due to the failure of another part ($).

C_{MT} Time required complete corrective actions (hrs).

D_{FT} Due fine time (hrs).

Ch Cost of delay charges per unit ($).

t_{tc} Time spent by the maintenance personnel to repair failure(hrs).

X_1 Number of maintenance personnel.

S_{mh} Maintenance hourly rate ($).

S_{oh} Operator's hourly rate ($).

X_2 Number of operational personnel.

P_{mc} Indicates the preventive maintenance cost that is required to preventive the failure and calculated by the developed equation (7-11) which has been extensively demonstrated in Chapter Five

$$P_{mc} = \{\left(\sum_{i=1}^{n} c_{sp_n} \times Prp_n\right) + \left(X_1 \times S_{mh} \times t_{ip}\right) + C_{wp} + C_{oh}\} \quad \text{7-11}$$

Where:-

C_{sp} Cost of spare parts ($).

Prp Possibility of replacing the part (%).

X_1 Number of maintenance personnel.

S_{mh} Maintenance personnel hourly rate ($/h).

t_{ip} Time spent by maintenance personnel carrying out PM (hrs).

C_{wp} Waste disposable cleaning cost ($).

C_{oh} Cost of out-house maintenance ($).

7.2.2.3 Human Health Loss

The consequences of failure on human health loss or factor (C) are estimated for each accident by the use of equation (7-12).

$$C = (AR) \times (PDI)/UFR \quad \text{7-12}$$

Where: -

AR Area under the damage radius (m^2).

UFR Unacceptable fatality rate "suggested value 10^{-3} (person) by Khan and Haddara (2003).

PDI Population density in the vicinity of the event (Persons/m^2)

$$PDI = PD1 \times PDF1 \qquad 7\text{-}13$$

Where:-

PD1 Number of people within the radius of impacted area.

PDF1 Population distribution factor that reflects the heterogeneity of the population distribution within the impacted area. Hirst and Carter (2000) assigned two values for this factor:-

The factor is substituted as 1 if the population is uniformly distributed within 500m radius; 0.2 If the population is localized away from the point of accident.

7.2.2.4 Environment Loss

The impact of failure on ecology (factor D) can be estimated by the use of the equation (7-14).

$$D = (AR) \times (IM)/UDA \qquad 7\text{-}14$$

Where:-

UDA Unacceptable damaging (m^2). This value of this parameter may change from one case to another due to the estimated damaged area which can be assumed following three possible methods

1. Historical data from the equipment or similar equipment.
2. Manufacturing recommendations.
3. Expert's estimation.

IM Impact factor and if the damage radius is greater than the distance between an accident and the location of the ecosystem. This parameter can be quantified using figure (7-2) (Khan and Haddara 2003).

Figure 7-2: Quantification of Importance Factor (IM) (Khan and Haddara 2003)

7.3 Applications of the Proposed Risk Assessment Method

In this section, application of the proposed risk estimation is applied on two parts (Mixer 100 and Valve 101) of high pressure separator (Khan and Haddara 2004). The assumption made for this application is the result of the qualitative assessment for the likelihood of the risk is equal and therefore is not discussed in this application.

Table (7-3) demonstrates the failure frequency of the selected parts. Mixer 101 averages mean time between failure (MTBF) is 6667 hrs (9.26 months) and Valve 101 (8.90 months). The outcome of the applied proposed LOR and its recommendations for the inspection intervals will be compared to the average MTBF of the parts in order to estimate the validity of the proposed model in this aspect.

Table 7-3: Spare Parts Average MTBF

Unit Number	Unit Name	Failure Frequency(per Hour)
1	Mixer 100	6667
2	Valve 102	6410

7.3.1 Application (1): Mixer 100

7.3.1.1 LOR for Mixer 100

Table (7-4) demonstrates the implementation of the developed mathematical equation to quantify the likelihood of risk (LOR) by considering the growth factor (G) factor and the physical life of assets. Mixer 100 physical life is considered to be (9 months).

Table 7-4: LOR and Growth Factor (G) for Mixer 100

T	G	LOR	T	G	LOR	T	G	LOR
0.1	0.011	0.0001	3.1	0.344	0.1189	6.1	0.678	0.5689
0.2	0.022	0.0004	3.2	0.356	0.1278	6.2	0.689	0.5911
0.3	0.033	0.0009	3.3	0.367	0.1370	6.3	0.700	0.6138
0.4	0.044	0.0015	3.4	0.378	0.1466	6.4	0.711	0.6371
0.5	0.056	0.0024	3.5	0.389	0.1566	6.5	0.722	0.6608
0.6	0.067	0.0035	3.6	0.400	0.1670	6.6	0.733	0.6851
0.7	0.078	0.0048	3.7	0.411	0.1778	6.7	0.744	0.7098
0.8	0.089	0.0064	3.8	0.422	0.1890	6.8	0.756	0.7351
0.9	0.100	0.0082	3.9	0.433	0.2006	6.9	0.767	0.7609
1	0.111	0.0102	4	0.444	0.2126	7	0.778	0.7872
1.1	0.122	0.0125	4.1	0.456	0.2251	7.1	0.789	0.8140
1.2	0.133	0.0150	4.2	0.467	0.2379	7.2	0.800	0.8414
1.3	0.144	0.0177	4.3	0.478	0.2512	7.3	0.811	0.8692
1.4	0.156	0.0208	4.4	0.489	0.2650	7.4	0.822	0.8976
1.5	0.167	0.0241	4.5	0.500	0.2792	7.5	0.833	0.9265
1.6	0.178	0.0277	4.6	0.511	0.2938	7.6	0.844	0.9560
1.7	0.189	0.0316	4.7	0.522	0.3088	7.7	0.856	0.9860
1.8	0.200	0.0357	4.8	0.533	0.3243	7.8	0.867	1.0165
1.9	0.211	0.0402	4.9	0.544	0.3403	7.9	0.878	1.0475
2	0.222	0.0449	5	0.556	0.3568	8	0.889	1.0791
2.1	0.233	0.0500	5.1	0.567	0.3736	8.1	0.900	1.1111
2.2	0.244	0.0554	5.2	0.578	0.3910	8.2	0.911	1.1438
2.3	0.256	0.0611	5.3	0.589	0.4088	8.3	0.922	1.1769
2.4	0.267	0.0671	5.4	0.600	0.4272	8.4	0.933	1.2106
2.5	0.278	0.0735	5.5	0.611	0.4459	8.5	0.944	1.2448
2.6	0.289	0.0802	5.6	0.622	0.4652	8.6	0.956	1.2796
2.7	0.300	0.0872	5.7	0.633	0.4850	8.7	0.967	1.3149
2.8	0.311	0.0946	5.8	0.644	0.5052	8.8	0.978	1.3507
2.9	0.322	0.1023	5.9	0.656	0.5259	8.9	0.989	1.3871
3	0.333	0.1104	6	0.667	0.5472	9	1.000	1.4240

Figure (7-3) shows the behaviour of the probability of failure and LOR against the part's life ratio. It demonstrates that the LOR crosses the life ratio of the part at about 6.9 months (4968hrs) and reaches 100% at 7.8 months (5616hrs).

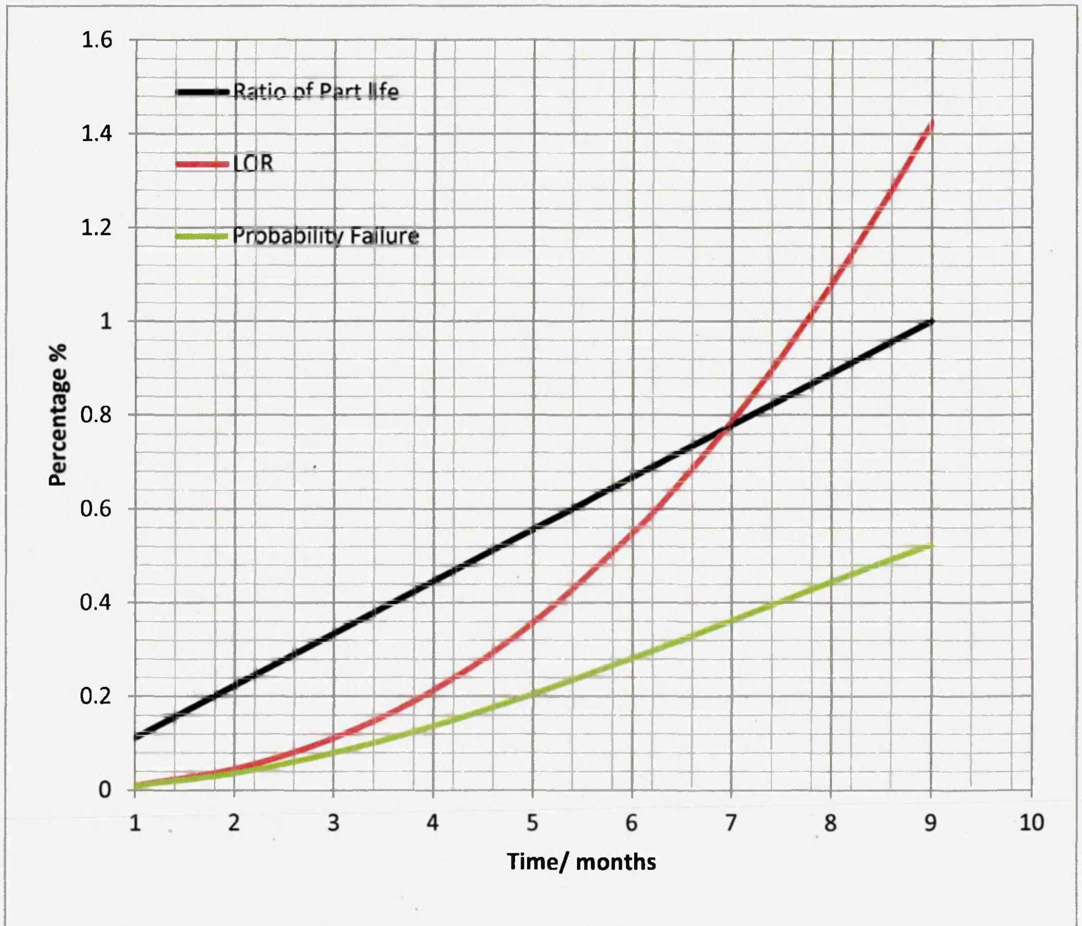


Figure 7-3: The Behaviour of LOR and Probability of Failure (Mixer 100)

The mean time between failures for Mixer 100 is 9.3 months. Likelihood of risk crosses the growth factor at (4968hrs) and reached 100% at (5616hrs). The advised interval inspection time is accordingly suggested to take place between 6.9 months and 7.8 months to ensure the part's health state can reach the next scheduled maintenance time(figure 7-4). In comparison with the reliance on the probability of the failure, LOR proposed mathematical equations shows better translation of understanding and estimating the inspection interval time. In terms of overlapping inspection jobs, the priority of the inspection is decided on the highest value of the consequences damages.

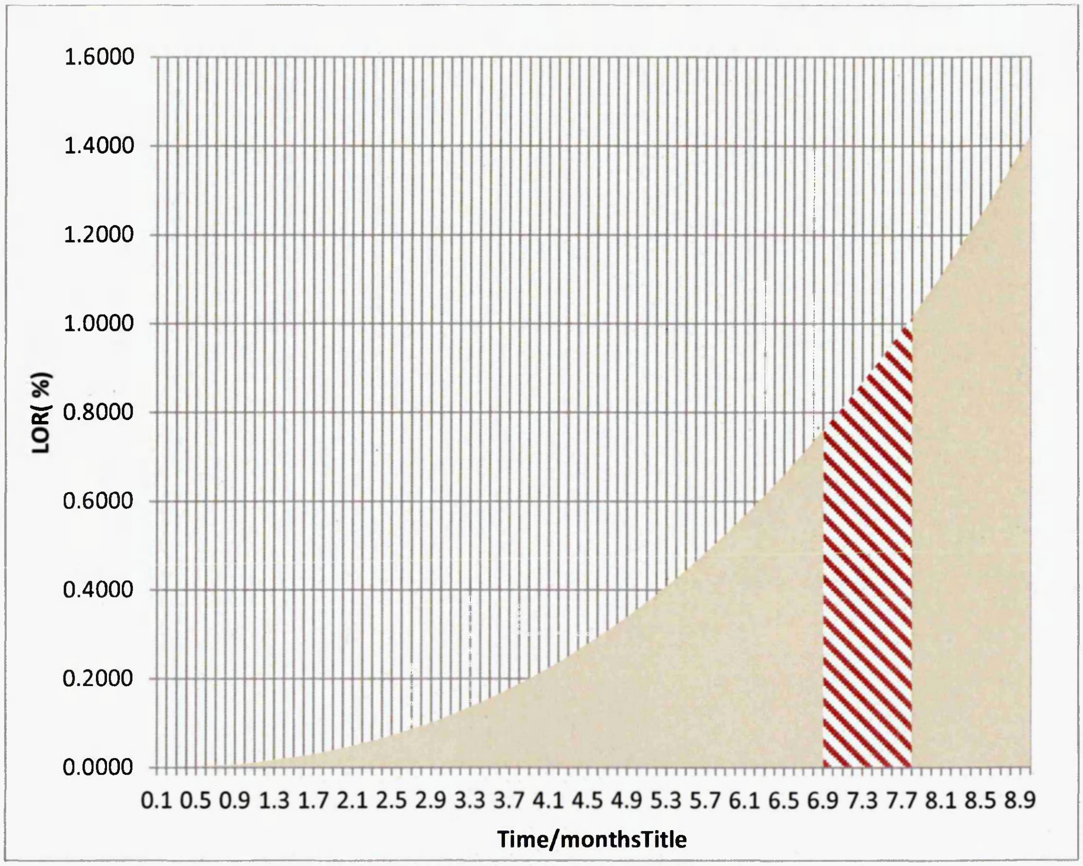


Figure 7-4: Optimum Inspection Interval for Mixer 100

7.3.1.2 Consequences of the Failure for the Mixer 100

Once the assessment of the likelihood of the risk is conducted the maintenance team should move to the estimation of the consequences of the failure.

Performance loss: - In this case, the assumption is that the failure of the mixer 100 would lead to the stoppage of the separator unit and therefore the performance loss would be classified as the highest (10).

Financial loss: - Equation (7-8) is applied to estimate the financial loss. Due to the fact that the failure of the equipment has got no financial impact in terms of fire and explosion leading to B_p to be considered having zero value. For the estimation of the incurred costs for the failure, equation (7-10) is applied and the related assumed cost in terms of the failure is listed in table (7-5). Few assumptions are presumed in order to apply equation (7-10) and (7-11):-

- The equipment has no alternative (stand-by equipment).
- Costs are calculated in US dollar.
- The equipment process 300 barrels a day.

Table 7-5: Related maintenance Costs (Mixer 100)

Cost	Value	Unit
Csp	500	$
Prp_n	100	%
Cwd	100	$
Soh	10	$/h
Smh	10	$/h
X_1	5	
X_2	5	
t_{tc}	5	hrs
t_{ti}	7	hrs
t_{su}	1	hrs
α	50	$
π	300/24= 0.08	$/h

Applying equation (7-10) of all expected and assumed costs in terms of corrective maintenance, we obtain the cost that may occur:-

$$C_{mc} = \{(500 \times \%100) + ((5+1) \times \left(\frac{50}{0.08}\right) + 100 + \left(\frac{5+1}{0.08}\right) + (5 \times 5 \times 10)$$

$$+ (5 + 1 \times 5 \times 10)$$

$$= 500 + 3750 + 100 + 75 + 250 + 300$$

$$C_{mc} = \$4975$$

Applying equation (7-11) we can calculate the preventive maintenance cost with the assumption that the production time loss is less (8h) in the case of corrective action. C_{wd} and $C_{oh}$are assumed to be zero:-

$$P_{mc} = (500 \times \%100) + (5 \times 10 \times 8)$$

$$P_{mc} = \$900$$

Therefore, substituting the values of C_{mc} and P_{mc} into equation (7-8)

$$B = \frac{4975 - 900}{900} = 4.53$$

The failure of the part has no environmental or human loss impact and therefore, substitute the determined values for the performance loss and the financial loss in equation (7-6)with the assumption that the weight given by the maintenance to prioritize the loss factors is equal (0.25):-

$$Consequence = \{(0.25 \times 10^2) + (0.25 \times 4.53^2)\}^{0.5}$$

$$Consequence = 5.49$$

7.3.2 Application (2): Valve 102

The failure frequency for the Valve 102 is 6410/hours and this value is converted into months (8.902 months).The designed life for Valve 102 is assumed as 9 months.

Table (7-6) demonstrates the time (T) in months, the growth factor (G) which is the result of dividing the increasing time by the designed age (9 months) and LOR, which approaches 100% of risk at just before 7.59 months.

Table 7-6: LOR and Growth Factor (G) for Valve 102

T	G	LOR	T	G	LOR	T	G	LOR
0.1	0.0111	0.0001	3.1	0.3444	0.1282	6.1	0.6778	0.6075
0.2	0.0222	0.0004	3.2	0.3556	0.1377	6.2	0.6889	0.6310
0.3	0.0333	0.0009	3.3	0.3667	0.1476	6.3	0.7000	0.6550
0.4	0.0444	0.0017	3.4	0.3778	0.1580	6.4	0.7111	0.6795
0.5	0.0556	0.0026	3.5	0.3889	0.1687	6.5	0.7222	0.7045
0.6	0.0667	0.0038	3.6	0.4000	0.1799	6.6	0.7333	0.7301
0.7	0.0778	0.0052	3.7	0.4111	0.1914	6.7	0.7444	0.7561
0.8	0.0889	0.0069	3.8	0.4222	0.2034	6.8	0.7556	0.7827
0.9	0.1000	0.0088	3.9	0.4333	0.2159	6.9	0.7667	0.8098
1	0.1111	0.0110	4	0.4444	0.2287	7	0.7778	0.8374
1.1	0.1222	0.0135	4.1	0.4556	0.2421	7.1	0.7889	0.8656
1.2	0.1333	0.0162	4.2	0.4667	0.2558	7.2	0.8000	0.8943
1.3	0.1444	0.0192	4.3	0.4778	0.2700	7.3	0.8111	0.9235
1.4	0.1556	0.0225	4.4	0.4889	0.2847	7.4	0.8222	0.9532
1.5	0.1667	0.0261	4.5	0.5000	0.2998	7.5	0.8333	0.9835
1.6	0.1778	0.0299	4.6	0.5111	0.3154	7.6	0.8444	1.0142
1.7	0.1889	0.0341	4.7	0.5222	0.3315	7.7	0.8556	1.0455
1.8	0.2000	0.0386	4.8	0.5333	0.3481	7.8	0.8667	1.0774
1.9	0.2111	0.0434	4.9	0.5444	0.3651	7.9	0.8778	1.1097
2	0.2222	0.0485	5	0.5556	0.3826	8	0.8889	1.1426
2.1	0.2333	0.0540	5.1	0.5667	0.4005	8.1	0.9000	1.1760
2.2	0.2444	0.0598	5.2	0.5778	0.4190	8.2	0.9111	1.2100
2.3	0.2556	0.0660	5.3	0.5889	0.4380	8.3	0.9222	1.2445
2.4	0.2667	0.0725	5.4	0.6000	0.4574	8.4	0.9333	1.2795
2.5	0.2778	0.0793	5.5	0.6111	0.4773	8.5	0.9444	1.3150
2.6	0.2889	0.0865	5.6	0.6222	0.4978	8.6	0.9556	1.3510
2.7	0.3000	0.0941	5.7	0.6333	0.5187	8.7	0.9667	1.3876
2.8	0.3111	0.1021	5.8	0.6444	0.5402	8.8	0.9778	1.4247
2.9	0.3222	0.1104	5.9	0.6556	0.5621	8.9	0.9889	1.4623
3	0.3333	0.1191	6	0.6667	0.5846	9	1.0000	1.5004

Figure (7-5) demonstrates the comparison between the behaviour of the cumulative distribution function ($F\Delta t$) and likelihood of risk (LOR). The capture of the figure is taken until the assumed physical life time ends.

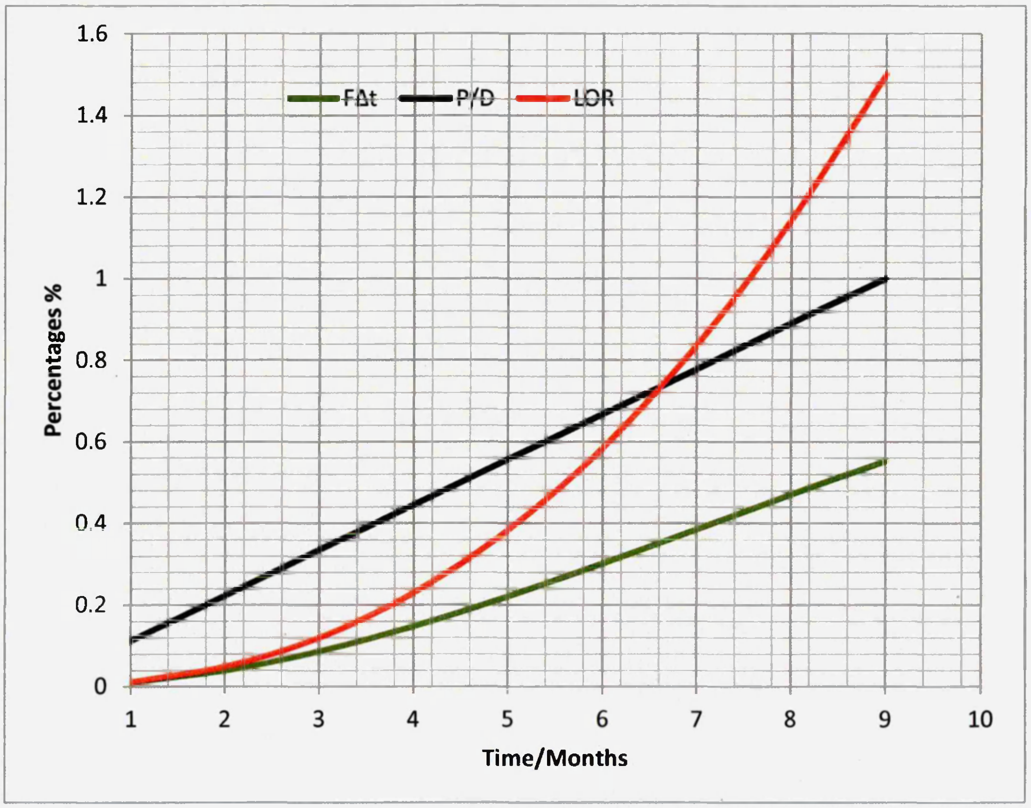


Figure 7-5: The Behaviour of LOR and Probability of Failure Valve 102

The consideration of the physical life of parts/equipment through the application of LOR assists in the prioritization of planning the inspection intervals maintenance intervention. The growth factor (G) crosses the LOR at almost 6.6 month (4752hrs) which is suggested the time of inspection until the time where LOR =100% at 7.59 months (5465hrs). In comparison with the MTBF of valve 102 (6410hrs) 8.90 months, the suggested time seems to leave enough time before the recorded average of MTBF. Figure (7-6) demonstrates the suggested inspection interval for valve 102. The designed life of part/equipment is a main parameter for the outcomes of LOR. In case of the two parts having the same value of probability of failure, the part with shorter designed life will be resulting in higher value of LOR, which leads to prioritizing it for inspection.

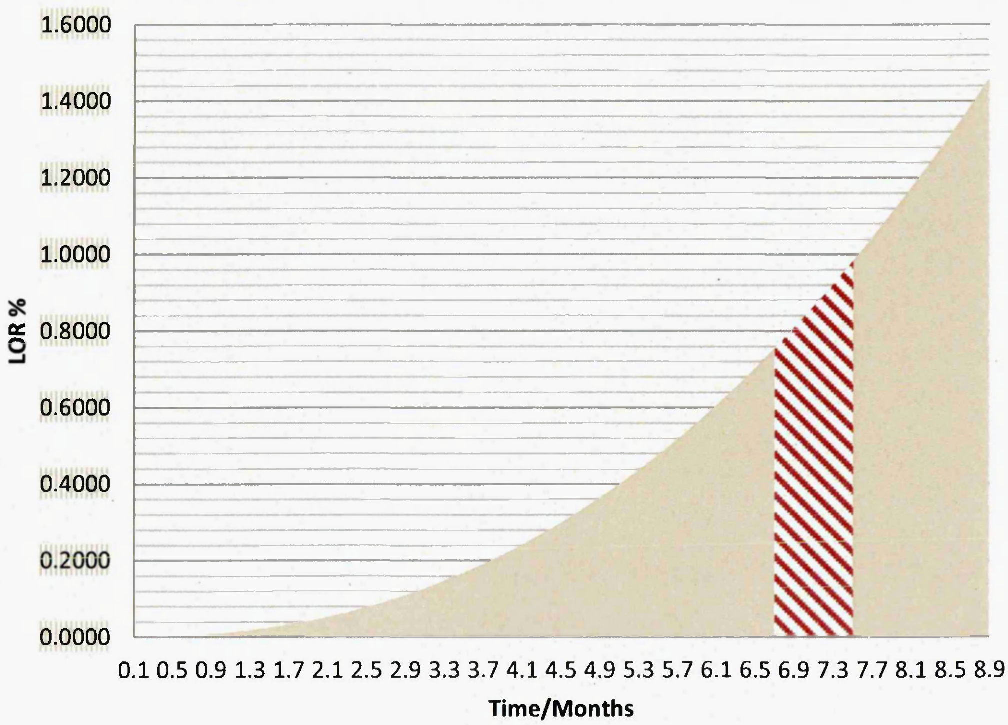


Figure 7-6: Optimum Inspection Interval for Valve 102

7.3.2.1 Consequences of the Failure for Valve 102

The consequences of the risk on the system performance loss are considered to be at the highest given the function of the valve and therefore are substituted as 10. Equation (7-8) is applied to calculate the financial loss under the assumption that the failure of the valve would cause explosion. The area under the damage (AR) is estimated 40 m^2 and the estimated assets density is 10000$/$m^2$.

$$Bp = ((40 \times 10000)/1000) \ = \ \$400$$

The corrective maintenance cost (C_{mc})and preventive maintenance cost P_{mc} that occurs due to the failure of valve 102 are assumed to be equal to the C_{mc} and P_{mc}that was calculated for mixer 100 which was$C_{mc} = \$4975$ and $P_{mc} = \$900$. Thus, the financial loss is computed as followed (equation 7-8)

$$B = \frac{(400 + 4975) - 900}{900}$$

$$B = 4.97$$

The human health loss factor is calculated by applying equation (7-12) and (7-13). The values of AR and UFR are (40 m^2) and (10^{-3} person) respectively. The population distribution factor PDF1 is substituted as (1) on the assumption that the population is localised within less than 500m and the number of people within that area is 10 persons. Thus:-

$$PDI = 10 \times 1 = 10\, persons/m^{2,}$$

Resulting into the human health loss (C)

$$C = (40 \times 10)/\, 10^{-3} = 400000$$

Equation (7-14) is applied to calculate the environmental loss (D), with AR 40 m^2 and from figure (7-2) IM is obtained (0.99). Unacceptable damaging level (UDA) is assumed to be $2m^2$ as the closest next equipment is placed close by. Thus:-

$$D = (40 \times 0.99)/2 = 19.8$$

The consequences damages are estimated by adding up the entire applied factors, using equation (7-6)

$$Consequence = \{(0.25 \times 10^2) + (0.25 \times 4.97^2) + (0.25 \times 400000^2) + (0.25 \times 19.8^2)\}^{0.5} = 200,000$$

If we assume that the consequences of the failure for both parts (Mixer 100 and Valve 102) were as resulted from, the above calculation (5.49 and 200,000 respectively then Valve 102 would be prioritized for maintenance action over Mixer 100. The weight of the loss factors would play a principal role in prioritizing the importance of the loss factors which would lead to different scenarios. For instance, for the Mixer 100 if the performance loss factor was weighted lower than the financial loss because of having stand by system, it would mean that the performance of the system would decrease but would not completely stopping the production.

7.4 Conclusion

In this chapter, the estimation of risk has been discussed and used to assess equipment health within the petroleum industry. The proposed model seek to assist into three main points

- Estimation of risk likelihood
- Optimisation of the inspection scheduling
- Evaluation of the consequences of risk into four areas

The proposed mathematical model for calculating Likelihood of Risk (LOR) to estimate the probability of risk has shown better reflection of the reality of the equipment risk's probability than the use of cumulative failure distribution. LOR and its consideration of the parameters of designed life and physical life (growth factor) help the inspector to prioritize the inspection intervals optimally. In the situation that both parts/equipment have the same failure distribution, the consequences would be impacted and different design life would play a decisive imperative role by prioritizing the shorter designed life component for inspection.

The application of LOR to identify the optimum inspection interval to determine whether the component will serve to the next maintenance interval or not show a promising results. In the two applications, the suggested intervals were identified with enough time before the MTBF by referencing to the cross of the growth factor to the time where LOR reached 100%.

The evaluation of the consequences for the four main loss areas: performance loss, financial loss, human loss and environment loss were considered in this work to estimate the consequences of the failure. The proposed consequences equation would allow more generalisation and accuracy of weighing the losses through the flexibility of the weight of the loss factors to avoid the shortages of having the same weight of loss with different scenarios as proposed by Khan and Haddara (2003). A modified equation was developed for the performance loss consequences that include the condition of having spare system to accurately simulate the performance loss of the production line.

The equation of the financial loss, which was originally proposed, by Khan and Haddara (2003), that considers the area of expected damage (AR) and the capacity of the equipment within that area (AD) has been further developed to involve the balance between costs of corrective actions and preventive actions. The analysis of the major related costs assists in alerting the maintenance team to have an estimation of the involved costs and the possibility of avoiding risk.

The contribution of this work to the assessment and estimation of the probability of risk and its consequences within the oil and gas industry can improve the responsiveness to the possibility of risk as well as providing better understanding of the impact of the risk on the major areas within this industry. Overall, this will particularly enhance the efficiency of maintenance by evaluating risk which is imperative to the nature of the petroleum industry.

Chapter Eight

Conclusions, Recommendations and Future Work

This chapter provides the concluding discussions of the research. It includes a discussion of research findings and their implications. The chapter summarises the contributions of the research to the knowledge in the field of maintenance in petroleum industry. Then the chapter ends with limitations and suggestions the future work.

8.1 Review of the Conducted Research

8.1.1 The Proposed Integrated Maintenance Framework

The main conception of the thesis is to optimise the major maintenance activities within the petroleum industry. To achieve this target, an integrated framework was created to comprehensively include major activities that maintenance function is involved in within the petroleum industry to guide this project. The framework investigates the selection of the most appropriate maintenance policy on the strategic level, considering all the relevant factors influencing this selection. As the major activities of maintenance within the petroleum industry are carried out on predefined intervals, the second level (maintenance operational level) is designed to carry on this activity. The outcome of the operational level is an optimum maintenance interval, which is then linked to the activity of risk assessment to obtain the inspection time and study the risk of the equipment. The outputs of the risk assessment are linked back to the operational level and the strategic level. The determination of the spare parts required by the maintenance is generated by the integrated approach between preventive maintenance, where most of the spare parts are consumed and spare parts control.

The proposed integrated framework demonstrates clear guidance to collaborate between the major activities of maintenance within the petroleum industry to optimise the maintenance actions in terms of reliability, risk, availability and cost-effectiveness.

8.1.2 Maintenance Strategic Level

On the strategic level, the problem of selecting the most suitable maintenance policy and assigning it to equipment or its parts was discussed.

The modelling of the problem using multi-criteria decision-making method (AHP) was applied and the structure of the criteria and sub-criteria that drives the decision-maker to select a particular maintenance policy and possible alternatives were identified. Both classic and fuzzy derivation methods were applied to understand the sensitivity of the methods in response to the changes in the preferences.

The proposed created model included the main criteria that concerns the selection of the maintenance policy, given the diversity of equipment and different required levels of reliability, availability and safety. The highlight of the proposed model is that it comprehensively embodies the most commonly used methodologies such as: reliability-centred maintenance and risk based maintenance by representing them in the form of criterion. In addition to that, the decomposition of the problem, which in this case is "selection of maintenance policy", provides the maintenance team with the a clear vision of reasoning of the selection of the alternatives, giving the advantage of quick response to changes in the circumstances that may lead to change in the maintenance policy. Since the model widely considers the major criteria, their sub-criteria and the possible maintenance policies, it can be applied to any section of the oil and gas production line from upstream to downstream.

8.1.3 Maintenance Operation Level

Chapter (5) addressed the difficulty of scheduling preventive maintenance activities (operational level) for equipment within the oil and gas industry and a developed mathematical model was introduced. The development of the model included the identification of the relevant maintenance costs that represent the nature cost of maintenance within the petroleum industry.

The equations of costs of corrective and preventive maintenance were modified in order to achieve this target. For instance, the probability of replacement parts, fees due to delay in delivering the product and cost of environmental cleaning and out-house maintenance cost were considered. The outcome of the mathematical model shows promising results in terms of reducing the cost of maintenance activities and without compromising on reliability of assets. The results were then compared with the historical data of failure to ensure that the advised maintenance interval does not suggest conducting maintenance after the occurrence of the failure and all obtained times were encouraging.

The operational availability of equipment, was remarkably improved. The sensitivity analysis proved the importance of the developed costs to simulate the real scenario, by showing the impact of the change on the cost of PM and CM. The applications showed that higher the cost of PM over the cost of CM, the longer the mean time between maintenance will be. The logical explanation of the sensitivity analysis suggests that, if CM cost is less than PM cost, then the part should be run until failure occurs. This again proves the importance of considering the major costs of failure within the oil and gas industry, as any miscalculation would result in the selection of an incorrect maintenance interval.

In conclusion, the proposed model for identifying the selection of maintenance policy within the petroleum industry included all the major aspects and factors, leading to the appropriate selection of maintenance policies.

8.1.4 Proposed Integrated Approach between Preventive Maintenance and Spare Parts Inventory

Chapter (6) covered the proposed integrated approach between the optimised maintenance intervals and the inventory management of spare parts to minimise the total inventory cost without impacting the availability of spare parts. The approach relied on optimising the preventive maintenance interval to calculate the demands of spare parts and applying the data to control spare parts availability within the stock.

The application of the proposed approach were applied with different assumptions of lead time restrictions and compare to the existing inventory policy. The outputs of the integrated approach demonstrated promising results in terms of smooth reordering cycle, while guaranteeing the availability of spare parts at the time of maintenance, avoiding erratic movement of spare parts, providing the possibility of predictability of future movement of spare parts and allowing the treatment of any shortage expected by increasing either the safety stock or the EOQ and decreasing the overall cost of inventory by decreasing the total annual average of the spare parts.

In summary, the availability of spare parts is imperative for the success of sustainable maintenance operations. The risk of shortages in supplying the maintenance with the spare parts demand could result in costly operation stoppages, while overstocking can lead to additional inventory costs. The proposed approach improves the integration between PM and spare parts control to eliminate the risk of shortage supply and overstocking, creating a cost effective approach.

8.1.5 Proposed Risk Assessment Model for the Petroleum Equipment

Chapter (7) dealt with the activity of assessing the risk for equipment within the petroleum industry. A proposed mathematical model for calculating the likelihood of risk (LOR) was introduced to estimate the probability of the risk. The model involved the growth factor, which considers the life expectancy of parts. The applications of the model demonstrated good results leading to advices to prioritize the inspection intervals optimally.

The consequences of expected failure were estimated to influence four main areas - "performance loss, financial loss, human loss and environment loss". A modified equation was developed for assessing the consequences of performance loss to consider the condition of having standby system. Another equation was developed to consider the impact of risk on the financial loss for the petroleum equipment to enhance the existing models.

The results of applying the proposed model demonstrated practical ways in the selection of the inspection intervals and evaluating the probability of occurrence of risk, as well as precise evaluation of the consequences of risk.

8.2 Research Contribution to knowledge

The research in this thesis has established a concrete framework through which maintenance activities within the petroleum industry can be optimised. The clear benefits and the uniqueness of the proposed models and integration approach is their practicality in real life. The key contributions to knowledge of this thesis can be summarised as follows:-

- An integrated maintenance framework to plan and control the major activities of maintenance and their interactions.

- A proposed model on the strategic level for the selection of the most appropriate maintenance policies considering the relevant factors within the petroleum industry and application of classic and fuzzy AHP.
- A cost optimisation mathematical model that balance between the cost of failure of a unit during operation against the cost of planned/preventive maintenance to schedule the preventive maintenance activities at the minimum possible cost without compromising on the utilisation of equipment's performance.
- An integrated approach between preventive maintenance and spare parts control to minimise the total inventory cost and ensure availability of spare parts when maintenance is performed.
- A risk assessment model for equipment within the petroleum industry and a new mathematical equation to assess the likelihood of risk and identifying the optimum inspection interval.
- A modified mathematical equation to evaluate consequences of risk which allow more generalisation and accuracy of weighing the losses.

8.3 Limitations

In this research, some limitation where distinguished while carrying out this work. The limitations can be summarised as followed:-

- The collection of the data of the preventive and corrective costs was quite difficult as the policy of the Oil and Gas Company was strict on revealing some relevant information such as the maintenance personnel's wages. However, an estimation of the average cost was provided.

- Another considered limitation is the scheduling of preventive maintenance and the inability of applying it on a production line that contains multi equipment because of the limited time to find a company to agree to that. This would have brought comprehensive details of the comparison between the outcomes of the mathematical model and the manufacturer recommendations.

8.4 Future Work

In the course of this research, even though there were many new developments in terms of framework, model, and integration approach, however, it was still possible to identify several areas for future research within the scope of this research. Few recommendations are suggested for future work as follows:-

- The applications of the maintenance interval is required to be applied on different equipment within the same production line to validate the grouping of the maintenance intervals.
- The integration between the condition based maintenance and spare parts control in terms of identifying an appropriate spare parts policy to control the stock quantity.
- Development of a software prototype to facilitate the application of the proposed models and integration approaches proposed in this research work.
- The conflict between the maintenance department and production department needs to be investigated in terms of for instance, responsibility of machine health.

- Conduct more applications of the proposed framework, models and integration approaches to further weight to the conclusions that were reached.
- An investigation into the risk assessment model within the petroleum industry that consider the existed local regulations and laws and their impact on the maintenance work.

References

Achilla, Mark e., Muchiri, Meter n. And Ikua, Bernard B. (2015). Selecting an Appropriate Maintenance Policy for Petroleum Pipeline System using AHP: A case study. *Journal of sustainable research in engineering vol,* 2 (1), 17-22.

Adebimpe, Oa, Oladokun, V. and Charles-Owaba, Oe (2015). Preventive Maintenance Interval Prediction: a Spare Parts Inventory Cost and Lost Earning Based Model. *Engineering, technology & applied science research,* 5 (3), pp. 811-817.

Ahmad, R., et al. (2011). Maintenance management decision model for preventive maintenance strategy on production equipment. *J.ind.eng.int,* 7 (13), 22-34.

Aissani, Nassima, Beldjilali, Bouziane and Trentesaux, Damien (2009). Dynamic scheduling of maintenance tasks in the petroleum industry: A reinforcement approach. *Engineering applications of artificial intelligence,* 22 (7), 1089-1103.

Akinci, Halil, Özalp, Ayşe Yavuz and Turgut, Bülent (2013). Agricultural land use suitability analysis using GIS and AHP technique. *Computers and electronics in agriculture,* 97 , 71-82.

American Petroleum Institute .(2000). Base resource documentation for risk based inspection (1st ed.). Washington, DC, USA: API Publication 581.

Al-Najjar, Basim and Alsyouf, Imad (2003). Selecting the most efficient maintenance approach using fuzzy multiple criteria decision making. *International journal of production economics,* 84 (1), 85-100.

Alonso, Jose Antonio and Lamata, M. Teresa (2006). Consistency in the analytic hierarchy process: a new approach. *International journal of uncertainty, fuzziness and knowledge-based systems,* 14 (04), 445-459.

Ambituuni, Ambisisi, Amezaga, Jaime M. and Werner, David (2015). Risk assessment of petroleum product transportation by road: A framework for regulatory improvement. *Safety science,* 79 , 324-335.

Andersen, Siri and Mostue, Bodil Aamnes (2012). Risk analysis and risk management approaches applied to the petroleum industry and their applicability to IO concepts. *Safety science,* 50 (10), 2010-2019.

Anderson, Dennis J., Carter, Charles M. and BROWN, Tamara (2015). Complexities of system of systems operational availability modeling. In: *Reliability and maintainability symposium (RAMS), 2015 annual,* IEEE, 1-6.

Anvaripour, Bagher, et al. (2013). Risk Analysis of Crude Distillation Unit's assets in Abadan Oil Refinery Using Risk Based Maintenance. *TJEAS journal,* 3 (16), 1888-1892.

Arendt, JS (1990). Using quantitative risk assessment in the chemical process industry. *Reliability engineering & system safety,* 29 (1), 133-149.

Aronis, Kostas-Platon, et al. (2004). Inventory control of spare parts using a Bayesian approach: A case study. *European journal of operational research,* 154 (3), 730-739.

Arunraj, Ns and Maiti, J. (2007). Risk-based maintenance—Techniques and applications. *Journal of hazardous materials,* 142 (3), 653-661.

Ascher, He (1997). A full history proportional hazards model for preventive maintenance scheduling. *Quality and reliability engineering international,* 13 , 187-198.

Ayağ, Zeki and Özdemir, Rifat Gürcan (2006). A fuzzy AHP approach to evaluating machine tool alternatives. *Journal of intelligent manufacturing,* 17 (2), 179-190.

Aydin Keskin, Gulsen and Ozkan, Coskun (2012). Multiple criteria ABC analysis with FCM clustering. *Journal of industrial engineering,* 2013 .

Azadeh, a., Ebrahimipour, V. and Bavar, P. (2009). A pump FMEA approach to improve reliability centered maintenance procedure: the case of centrifugal pumps in onshore industry. In: *Proceedings of the 6th WSEAS international conference on FLUID MECHANICS (FLUIDS'09),* 38-45.

Bacchetti, A., et al. (2010). Spare parts classification and inventory management: a case study. *Salford business school working papers series,* 408 .

Bacchetti, Andrea and SACCANI, Nicola (2012). Spare parts classification and demand forecasting for stock control: Investigating the gap between research and practice. *Omega,* 40 (6), 722-737.

Balkey, Kenneth R., Art, Raymond J. and Bosnak, Robert J. (1998). ASME Risk-Based Inservice Inspection and Testing: An Outlook to the Future. *Risk analysis,* 18 (4), 407-421.

Bertolini, M., et al. (2009). Development of risk-based inspection and maintenance procedures for an oil refinery. *Journal of loss prevention in the process industries,* 22 (2), 244-253.

Bertolini, Massimo and Bevilacqua, Maurizio (2006). A combined goal programming—AHP approach to maintenance selection problem. *Reliability engineering & system safety,* 91 (7), 839-848.

Bevilacqua, M., Ciarapica, FE and Giacchetta, G. (2008). Spare parts inventory control for the maintenance of productive plants. In: *Industrial engineering and engineering management, 2008. IEEM 2008. IEEE international conference on,* IEEE, 1380-1384.

Bevilacqua, Maurizio and Braglia, Marcello (2000). The analytic hierarchy process applied to maintenance strategy selection. *Reliability engineering & system safety,* 70 (1), 71-83.

Bošnjaković, Mladen (2010). Multicriteria inventory model for spare parts. *Tehnički vjesnik,* 17 (4), 499-504.

Bowersox, Donald J., Closs, David J., Cooper, M. Bixby and Bowersox, John C. (2013). Supply chain logistics management. 4th ed, McGraw-Hill, New York.

Calixto, Eduardo (2012). *Gas and Oil Reliability Engineering: Modeling and Analysis.* Gulf Professional Publishing.

Carter, DA, et al. (2003). Appropriate risk assessment methods for major accident establishments. *Process safety and environmental protection,* 81 (1), 12-18.

Cassady, C. Richard, Murdock, W. Paul and Pohl, Edward A. (2001). Selective maintenance for support equipment involving multiple maintenance actions. *European journal of operational research,* 129 (2), 252-258.

Chang, Da-Yong (1996). Applications of the extent analysis method on fuzzy AHP. *European journal of operational research,* 95 (3), 649-655.

Chang, Ming-Kuen, et al. (2005). Application of risk based inspection in refinery and processing piping. *Journal of loss prevention in the process industries,* 18 (4), 397-402.

Chelbi, Anis and AïT-Kadi, Daoud (2001). Spare provisioning strategy for preventively replaced systems subjected to random failure. *International journal of production economics,* 74 (1), 183-189.

Chen, Fei-Long, Chen, Yun-Chin and Kuo, Jun-Yuan (2010). Applying moving back-propagation neural network and moving fuzzy neuron network to predict the requirement of critical spare parts. *Expert systems with applications,* 37 (6), 4358-4367.

Cheng, Zhonghua, et al. (2008). A framework for intelligent reliability centered maintenance analysis. *Reliability engineering & system safety,* 93 (6), 806-814.

Chengzhong, Luo (1984). Extension principle and fuzzy number. *Fuzzy mathematics,* 3 , 109-116.

Chu, Ching-Wu, Liang, Gin-Shuh and Liao, Chien-Tseng (2008). Controlling inventory by combining ABC analysis and fuzzy classification. *Computers & industrial engineering,* 55 (4), 841-851.

Cigolini, Roberto and Rossi, Tommaso (2010). Managing operational risks along the oil supply chain. *Production planning and control,* 21 (5), 452-467.

Cinelli, Marco, Stuart R. Coles, and Kerry Kirwan. (2014) Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. *Ecological Indicators*, 46, 138-148.

Coetzee, Jasper L. (1997). The role of NHPP models in the practical analysis of maintenance failure data. *Reliability engineering & system safety,* 56 (2), 161-168.

Cohen, Morris A., Agrawal, Narendra and AGRAWAL, Vipul (2006). Winning in the aftermarket. *Harvard business review,* 84 (5), 129.

Cui, Li-Rong, Hayakawa, Yu and Obiajunwa, Christopher C. (2013). Skills for the management of turnaround maintenance projects. *Journal of quality in maintenance engineering,* 19 (1), 61-73.

Culp, Christopher L. (2002). *The risk management process: Business strategy and tactics.* John Wiley & Sons., 103.

Dawotola, Alex W., et al. (2012). Risk-based maintenance of a cross-country petroleum pipeline system. *Journal of pipeline systems engineering and practice,* 4 (3), 141-148.

Dawotola, Alex W., Van Gelder, Phajm and Vrijling, JK (2009). Risk Assessment of Petroleum Pipelines using a com-bined Analytical Hierarchy Process-Fault Tree Analysis (AHP-FTA).

Dawotola, Alex W., Van Gelder, Phajm and Vrijling, JK (2010). Multi Criteria Decision Analysis framework for risk management of oil and gas pipelines. *RELIABILITY, risk and safety.london: Taylor &francis group,* , 307-314.

De Smidt-Destombes, Karin S., van der Heijden, Matthieu C and Van Harten, Aart (2009). Joint optimisation of spare part inventory, maintenance frequency and repair capacity for k-out-of-N systems. *International journal of production economics,* 118 (1), 260-268.

Deshpande, VS and Modak, JP (2002). Application of RCM to a medium scale industry. *Reliability engineering & system safety,* 77 (1), 31-43.

Devold, Havard (2013). *Oil and gas production handbook: an introduction to oil and gas production.* Lulu. com.

Dey, Prasanta K. (2001). A risk-based model for inspection and maintenance of cross-country petroleum pipeline. *Journal of quality in maintenance engineering,* 7 (1), 25-43.

Dey, Prasanta Kumar, OGUNLANA, Stephen O. and NAKSUKSAKUL, Sittichai (2004). Risk-based maintenance model for offshore oil and gas pipelines: a case study. *Journal of quality in maintenance engineering,* 10 (3), 169-183.

Dhillon, Balbir S. (2002). *Engineering maintenance: a modern approach.* CRC Press.

Doostparast, Mohammad, Kolahan, Farhad and Doostparast, Mahdi (2014). A reliability-based approach to optimize preventive maintenance scheduling for coherent systems. *Reliability engineering & system safety,* 126 , 98-106.

Driessen, Maarten, et al. (2014). Maintenance spare parts planning and control: A framework for control and agenda for future research. *Production planning & control,* (ahead-of-print), 1-20.

Drury, Colin M. (2013). *Management and cost accounting.* Springer.

Duffuaa, SO, Raouf, A. and Campbell, J. (1999). Maintenance Planning and Control: Modeling and Analysis.

El-Jawhari B and Collins P (2014). Improve maintenance productivity: Close the gap between 'should take' and 'does take' in refinery maintenance.[Onlin] http://www.arcadis.com/Content/ArcadisGlobal/Docs/publications/Research/8965_ARCADIS_Oil_and_Gas_Operational_excellence_FINAL.pdf (accessed 27 October 2015).

Eroglu, Cuneyt and Hofer, Christian (2011). Inventory types and firm performance: Vector autoregressive and vector error correction models. *Journal of business logistics,* 32 (3), 227-239.

Eti, Mark C., Ogaji, Sot and Probert, SD (2006). Development and implementation of preventive-maintenance practices in Nigerian industries. *Applied energy,* 83 (10), 1163-1179.

EVANS, JR (2007) Production/operations management, quality, performance and value: Operations scheduling and production-activity control.

Fiegler, Anja, et al. (2013). Advanced Quality Measurement for Cloud Services. In: *Cloud computing (CLOUD), 2013 IEEE sixth international conference on,* IEEE, 786-793.

Fleischer, Jürgen, Weismann, Udo and Niggeschmidt, Stephan (2006). Calculation and optimisation model for costs and effects of availability relevant service elements. *Proceedings of LCE,* , 675-680.

Forman, Ernest H. (1990). Random indices for incomplete pairwise comparison matrices. *European journal of operational research,* 48 (1), 153-155.

Gabbar, Hossam A., et al. (2003). Computer-aided RCM-based plant maintenance management system. *Robotics and computer-integrated manufacturing,* 19 (5), 449-458.

Gandhare, Balasaheb S. and Akarte, Milind (2012). Maintenance strategy selection. In: *Proceedings of the ninth AIMS international conference on management, pune,* 1330-1336.

Gopalakrishnan, P. and Banerji, AK (2013). *Maintenance and spare parts management.* PHI Learning Pvt. Ltd.

Griggs, John Wyeth (2011). BP Gulf of Mexico oil spill. *Energy LJ,* 32 , 57.

Gupta, R., et al. (2007). ABC and VED analysis in medical stores inventory control. *Medical journal armed forces india,* 63 (4), 325-327.

Guvenir, H. Altay and Erel, Erdal (1998). Multicriteria inventory classification using a genetic algorithm. *European journal of operational research,* 105 (1), 29-37.

Hadi-Vencheh, A. and Mohamadghasemi, A. (2011). A fuzzy AHP-DEA approach for multiple criteria ABC inventory classification. *Expert systems with applications,* 38 (4), 3346-3352.

Hauge, Kjellrun Hiis, et al. (2014). Inadequate risk assessments–A study on worst-case scenarios related to petroleum exploitation in the Lofoten area. *Marine policy,* 44 , 82-89.

Heizer, Jay H. and Render, Barry (2014). *Principles of Operations Management: Sustainability and Supply Chain Management.* Prentice Hall.

Hirst, IL and CARTER, DA (2000). A "worst case" methodology for risk assessment of major accident installations. *Process safety progress,* 19 (2), 78-85.

Hu, Qiwei, et al. (2013). The joint optimisation model for spare part demand and maintenance cost under compound maintenance strategy. In: *Quality, reliability, risk, maintenance, and safety engineering (QR2MSE), 2013 international conference on,* IEEE, 1249-1252.

Hua, ZS, et al. (2007). A new approach of forecasting intermittent demand for spare parts inventories in the process industries. *Journal of the operational research society,* 58 (1), 52-61.

International Programme on Chemical Safety and World Health Organization (2004). *IPCS risk assessment terminology.* World Health Organization.

IQPC (2014). The economic impact from a number of unplanned shutdowns can be severe for oil and gas companies.[onlin] http://www.stoasia.com/ (accessed 25 October 2015).

Ishizaka, Alessio and Labib, Ashraf (2009). Analytic hierarchy process and expert choice: Benefits and limitations. *OR insight,* 22 (4), 201-220.

Ishizaka, Alessio and Lusti, Markus (2006). How to derive priorities in AHP: a comparative study. *Central european journal of operations research,* 14 (4), 387-400.

Işiklar, Gülfem and Büyüközkan, Gülçin (2007). Using a multi-criteria decision making approach to evaluate mobile phone alternatives. *Computer standards & interfaces,* 29 (2), 265-274.

Işiklar, Gülfem and Büyüközkan, Gülçin (2007). Using a multi-criteria decision making approach to evaluate mobile phone alternatives. *Computer standards & interfaces,* 29 (2), 265-274.

Jagathy Raj, VP and Deepak Prabhakar, P. (2013). A New Model For Reliability Centered Maintenance In Petroleum Refineries.

Jiang, Yunpeng, Chen, Maoyin and Zhou, Donghua (2015). Joint optimisation of preventive maintenance and inventory policies for multi-unit systems subject to deteriorating spare part inventory. *Journal of manufacturing systems,* 35 , 191-205.

Jingjiang, Gao and Zhendong, Hao (2012). A classification model for inventory management of spare parts and its application. In: *Industrial control and electronics engineering (ICICEE), 2012 international conference on,* IEEE, 592-595.

Kabir, Abm Zohrul and Al-Olayan, Ahmed S. (1996). A stocking policy for spare part provisioning under age based preventive replacement. *European journal of operational research,* 90 (1), 171-181.

Kabir, Golam and Hasin, M. Ahsan Akhtar (2011). Comparative analysis of AHP and Fuzzy AHP models for multicriteria inventory classification. *International journal of fuzzy logic systems,* 1 (1), 1-16.

Kainulainen, T., et al. (2009). A statistical approach to assessing interval scale preferences in discrete choice problems. *Journal of the operational research society,* 60 (2), 252-258.

Kaio, Naoto and Osaki, Shunji (1981). Optimum planned maintenance policies with lead time. *IEEE transactions on reliability,* 1 , 79.

Kelton, Sadowski (2007). Sturrock (2007)"Simulation with arena".

Kennedy, Wj, Patterson, J. Wayne and Fredendall, Lawrence D. (2002). An overview of recent literature on spare parts inventories. *International journal of production economics,* 76 (2), 201-215.

Keth, L., Muhlemen, A. and Oakland, J. (1994). Production and operations management. London, Pitman Publisher.

Khalil, Jean, Saad, Sameh M. and Gindy, Nabil (2009). An integrated cost optimisation maintenance model for industrial equipment. *Journal of quality in maintenance engineering,* 15 (1), 106-118.

Khan, Faisal I. and Haddara, Mahmoud (2004). Risk-based maintenance (RBM): A new approach for process plant inspection and maintenance. *Process safety progress,* 23 (4), 252-265.

Khan, Faisal I. and Haddara, Mahmoud M. (2003). Risk-based maintenance (RBM): a quantitative approach for maintenance/inspection scheduling and planning. *Journal of loss prevention in the process industries,* 16 (6), 561-573.

Khan, Faisal I., IQBAL, Asad and Abbasi, SA (2001). Risk analysis of a petrochemical industry using ORA (Optimal Risk Analysis) procedure. *Process safety progress,* 20 (2), 95-110.

Khan, Faisal Irshad and Abbasi, Shahid Abbas (1998). *Risk assessment in chemical process industries.* Discovery Publishing House.

Knezevic, Jezdimir, et al. (2012). Shutdown preparedness in oil and gas production. *Journal of quality in maintenance engineering,* 18 (2), 154-170.

Krajewski, Lee J., Malhotra, Manoj K. and Ritzman, Larry P. (2015). *Operations management: processes and supply chains.* Prentice Hall.

Krishnasamy, Loganathan, Khan, Faisal and Haddara, Mahmoud (2005). Development of a risk-based maintenance (RBM) strategy for a power-generating plant. *Journal of loss prevention in the process industries,* 18 (2), 69-81.

Kwong, CK and Bai, H. (2002). A fuzzy AHP approach to the determination of importance weights of customer requirements in quality function deployment. *Journal of intelligent manufacturing,* 13 (5), 367-377.

Kundi, G. M., and Asadullah, M. (2013). International Journal of Business Management and Administration. An analysis of the use of heuristics to understand the dynamics of modern decision making, Vol. 2(4), pp. 064-068Lane, Eric F. and Verdini, William A. (1989). A consistency test for AHP decision makers. *Decision sciences,* 20 (3), 575-590.

Lee, C. and Teo, Y. (2001). Det Norske Veritas RBI study for the ammonia storage plant. *Taiwan, ROC: Taiwan fertilizer kaohsiung ammonia terminal,* .

Leou, Rong-Ceng (2006). A new method for unit maintenance scheduling considering reliability and operation expense. *International journal of electrical power & energy systems,* 28 (7), 471-481.

Li, Jing Rong, Khoo, Li Pheng and Tor, Shu Beng (2006). Generation of possible multiple components disassembly sequence for maintenance using a disassembly constraint graph. *International journal of production economics,* 102 (1), 51-65.

Liao, Haitao and Rausch, Mitchell (2010). Spare part inventory control driven by condition based maintenance. In: *Reliability and maintainability symposium (RAMS), 2010 proceedings-annual,* IEEE, 1-6.

Lin, Shi-Woei and Lu, Ming-Tsang (2012). Characterizing disagreement and inconsistency in experts' judgments in the analytic hierarchy process. *Management decision,* 50 (7), 1252-1265.

Louit, Darko, et al. (2011). Optimization models for critical spare parts inventories—a reliability approach. *Journal of the operational research society,* 62 (6), 992-1004.

Luxhøj, James T., RIIS, Jens O. and Thorsteinsson, Uffe (1997). Trends and perspectives in industrial maintenance management. *Journal of manufacturing systems,* 16 (6), 437-453.

Madu, Christian N. (2000). Competing through maintenance strategies. *International journal of quality & reliability management,* 17 (9), 937-949.

Malczewski, Jacek (1999). *GIS and multicriteria decision analysis.* John Wiley & Sons.

Mann, Lawrence, Saxena, Anuj and Knapp, Gerald M. (1995). Statistical-based or condition-based preventive maintenance? *Journal of quality in maintenance engineering,* 1 (1), 46-59.

Márquez, Adolfo Crespo (2007). *The maintenance management framework: models and methods for complex systems maintenance.* Springer Science & Business Media.

Maylor, Harvey. (2010). Project management. 4th ed., Harlow, Financial Times Prentice Hall.

Mearns, Kathryn and Yule, Steven (2009). The role of national culture in determining safety performance: Challenges for the global oil and gas industry. *Safety science,* 47 (6), 777-785.

Meeker, William Q. and Escobar, Luis A. (2014). *Statistical methods for reliability data.* John Wiley & Sons.

Merna, Tony and Al-Thani, Faisal F. (2011). *Corporate risk management.* John Wiley & Sons.

Millstein, Mitchell A., Yang, Liu and LI, Haitao (2014). Optimizing ABC inventory grouping decisions. *International journal of production economics,* 148 , 71-80.

Mirghani, Mohamed Ali (2001). A framework for costing planned maintenance. *Journal of quality in maintenance engineering,* 7 (3), 170-182.

Mobley, R. Keith (2002). *An introduction to predictive maintenance.* Butterworth-Heinemann.

Molenaers, An, et al. (2012). Criticality classification of spare parts: A case study. *International journal of production economics,* 140 (2), 570-578.

Moubray, John (2000). The case against streamlined RCM. *Aladon, UK,* .

Muchiri, Peter, et al. (2011). Development of maintenance function performance measurement framework and indicators. *International journal of production economics,* 131 (1), 295-302.

Murthy, Dnp, Atrens, A. and Eccleston, JA (2002). Strategic maintenance management. *Journal of quality in maintenance engineering,* 8 (4), 287-305.

Nielsen, Jakob (1994). *Usability engineering.* Elsevier.

Özdağoğlu, Aşkın and Özdağoğlu, Güzin (2007). Comparison of AHP and fuzzy AHP for the multi-criteria decision making processes with linguistic evaluations.

Parida, Aditya and Kumar, Uday (2006). Maintenance performance measurement (MPM): issues and challenges. *Journal of quality in maintenance engineering,* 12 (3), 239-251.

Perçin, Selçuk (2008). Use of fuzzy AHP for evaluating the benefits of information-sharing decisions in a supply chain. *Journal of enterprise information management,* 21 (3), 263-284.

Percy, David F. and Kobbacy, Khairy AH (1996). Preventive maintenance modelling: a Bayesian perspective. *Journal of quality in maintenance engineering,* 2 (1), 15-24.

Perrons, Robert K. and Richards, Matthew G. (2013). Applying maintenance strategies from the space and satellite sector to the upstream oil and gas industry: A research agenda. *Energy policy,* 61 , 60-64.

Porras, Eric and Dekker, Rommert (2008). An inventory control system for spare parts at a refinery: An empirical comparison of different re-order point methods. *European journal of operational research,* 184 (1), 101-132.

Pradhan, Mk and Bhol, JP (2006). Trends and Perspectives in Industrial Maintenance Management.

Prakash, TN (2003). Land suitability analysis for agricultural crops: a fuzzy multicriteria decision making approach. *MS theses international institute for geo-information science and earth observation enschede, the netherland,* .

Ramanathan, Ramakrishnan (2006). ABC inventory classification with multiple-criteria using weighted linear optimization. *Computers & operations research,* 33 (3), 695-700.

Rausand, Marvin and HØYLAND, Arnljot (2004). *System reliability theory: models, statistical methods, and applications.* John Wiley & Sons. , 396.

Rausand, Marvin and VATN, Jørn (1998). Reliability modeling of surface controlled subsurface safety valves. *Reliability engineering & system safety,* 61 (1), 159-166.

Rausand, Marvin and VATN, Jørn (2008). Reliability centred maintenance. In: *Complex system maintenance handbook.* Springer, 79-108.

Ravitch, Sharon M. and Riggan, Matthew (2011). *Reason & rigor: How conceptual frameworks guide research.* Sage.

Reeves, Colin R. (1993). *Modern heuristic techniques for combinatorial problems.* John Wiley & Sons, Inc.

Reid, Robert D. and Sanders, Nada R. (2005). *Operations management: an integrated approach.* John Wiley Hoboken, NJ.

Reynolds, John T. (1996). *The application of risk-based inspection methodology in the petroleum and petrochemical industry,* .

Roberts, SM and Escudero, Lf (1983). Minimum problem-size formulation for the scheduling of plant maintenance personnel. *Journal of optimization theory and applications,* 39 (3), 345-362.

Ross, Timothy J. (2009). *Fuzzy logic with engineering applications.* John Wiley & Sons.

Rpsgroup (2011). Preventing Major Accidents in the. [online]. Last accessed 02 October 2015 at: http://www.rpsgroup.com/Energy/Services/Advisory/Downstream/pdf/RPS-Final-Hazard-White-Paper_Nov2010_combined.aspx

Ruoning, Xu and Xiaoyan, Zhai (1992). Extensions of the analytic hierarchy process in fuzzy environment. *Fuzzy sets and systems,* 52 (3), 251-257.

Saad M Sameh, Khan Nufal AND Mohamed Abdel.(2016). A fuzzy-AHP multi-criteria decision-making model for procurement process. *International Journal of Logistics Systems and Management*, Vol. 23, No. 1, 2016

Saad M Sameh, Cano Samuel, I. Basarab-Horwath Ivan, Khalil Jean and Pohi Thomas.(2004) "Minimisation of identical machines maintenance schedule cost". *The 2nd International Conference on Advances in Manufacturing Research*, 7-9 Sept 2004, UK

Saaty, Thomas L. (1977). A scaling method for priorities in hierarchical structures. *Journal of mathematical psychology,* 15 (3), 234-281.

Saaty, Thomas L. (1980). The analytic hierarchy process: planning, priority setting, resources allocation. *New york: McGraw,* .

Saaty, Thomas L.(1982). Decision making for leaders: The analytical hierarchical process for decisions in a complex world. Belmont. *CA: Wadsworth,* .

Saaty, Thomas L. (1990). How to make a decision: the analytic hierarchy process. *European journal of operational research,* 48 (1), 9-26.

Saaty, Thomas L. (1994). How to make a decision: the analytic hierarchy process. *Interfaces,* 24 (6), 19-43.

Saaty, Thomas L. (1997). That is not the analytic hierarchy process: what the AHP is and what it is not. *Journal of Multi-Criteria decision analysis,* 6 (6), 324-335.

Saaty, Thomas L. (2003). Decision-making with the AHP: Why is the principal eigenvector necessary. *European journal of operational research,* 145 (1), 85-91.

Saaty, Thomas L. (2008). Relative measurement and its generalization in decision making why pairwise comparisons are central in mathematics for the measurement of intangible factors the analytic hierarchy/network process. *RACSAM-revista de la real academia de ciencias exactas, fisicas y naturales.serie A.matematicas,* 102 (2), 251-318.

Saranga, Haritha (2002). Relevant condition-parameter strategy for an effective condition-based maintenance. *Journal of quality in maintenance engineering,* 8 (1), 92-105.

Sarfaraz, A., Mukerjee, P. and Jenab, K. (2012). Using fuzzy analytical hierarchy process (AHP) to evaluate web development platform. *Management science letters,* 2 (1), 253-262.

Scala, Natalie M., Rajgopal, Jayant and Needy, Kim LaScola (2014). Managing Nuclear Spare Parts Inventories: A Data Driven Methodology. *Engineering management, IEEE transactions on,* 61 (1), 28-37.

Schroeder, Roger G., Goldstein, Susan Meyer and Rungtusanatham, M. Johnny (2011). *Operations management: Contemporary concepts and cases.* McGraw-Hill.

Selvik, Jon T. and Aven, Terje (2011). A framework for reliability and risk centered maintenance. *Reliability engineering & system safety,* 96 (2), 324-331.

Sharma, Mithun J. and Yu, Song Jin (2014). Fuzzy analytic hierarchy process-based decision tree in identifying priority attributes for supply chain coordination. *International journal of logistics systems and management,* 17 (1), 46-65.

Shaverdi, Meysam and Barzin, Parakhat (2012). Applying fuzzy AHP to determination of optimum selection method for economic cocoon traits improvement in silkworm breeding.

Siew-Hong, Ding and Kamaruddin, Shahrul (2012). Selection of optimal maintenance policy by using fuzzy multi criteria decision making method. In: *Peresented at the 2012. internatonal conference on industrial engineering and operations management, istanbul turkey,* 435-443.

Syntetos, Aris A., Keyes, M. and Babai, MZ (2009). Demand categorisation in a European spare parts logistics network. *International journal of operations & production management,* 29 (3), 292-316.

Tang, Yang, et al. (2015). A framework for making maintenance decisions for oil and gas drilling and production equipment. *Journal of natural gas science and engineering,* 26 , 1050-1058.

Tixier, Jerome, et al. (2002). Review of 62 risk analysis methodologies of industrial plants. *Journal of loss prevention in the process industries,* 15 (4), 291-303.

Torfi, Fatemeh, Farahani, Reza Zanjirani and Rezapour, Shabnam (2010). Fuzzy AHP to determine the relative weights of evaluation criteria and Fuzzy TOPSIS to rank the alternatives. *Applied soft computing,* 10 (2), 520-528.

Tsang, Albert HC (2002). Strategic dimensions of maintenance management. *Journal of quality in maintenance engineering,* 8 (1), 7-39.

Tummala, Vm Rao and Wan, Yat-wah (1994). On the mean random inconsistency index of analytic hierarchy process (AHP). *Computers & industrial engineering,* 27 (1), 401-404.

Van Horenbeek, Adriaan, et al. (2013). Joint maintenance and inventory optimization systems: A review. *International journal of production economics,* 143 (2), 499-508.

Van Laarhoven, Pjm and Pedrycz, Witold (1983). A fuzzy extension of Saaty's priority theory. *Fuzzy sets and systems,* 11 (1), 199-227.

Vasumathi, B. and Saradha, A. (2013). Forecasting Intermittent Demand for Spare Parts. *International journal of computer applications,* 75 (11), 12-16.

Vaughan, Timothy S. (2005). Failure replacement and preventive maintenance spare parts ordering policy. *European journal of operational research,* 161 (1), 183-190.

Velasquez, Mark, and Patrick T. Hester. (2013). An analysis of multi-criteria decision making methods. *International Journal of Operations Research,* 10 (2), 56-66.

Vidal, Ludovic-Alexandre, Marle, Franck and Bocquet, Jean-Claude (2011). Using a Delphi process and the Analytic Hierarchy Process (AHP) to evaluate the complexity of projects. *Expert systems with applications,* 38 (5), 5388-5405.

Waeyenbergh, Geert and Pintelon, Liliane (2002). A framework for maintenance concept development. *International journal of production economics,* 77 (3), 299-313.

Waeyenbergh, Geert and Pintelon, Liliane (2004). Maintenance concept development: a case study. *International journal of production economics,* 89 (3), 395-405.

Wahba, Eman M., Galal, Noha M. and El-Kilany, Khaled S. (2012). Framework for Spare Inventory Management. In: *Proceedings of world academy of science, engineering and technology,* World Academy of Science, Engineering and Technology, .

Wang, Ling, Chu, Jian and Wu, Jun (2007). Selection of optimum maintenance strategies based on a fuzzy analytic hierarchy process. *International journal of production economics,* 107 (1), 151-163.

Waters, Donald (2008). *Inventory control and management.* John Wiley & Sons.

Wind, Yoram and Saaty, Thomas L. (1980). Marketing applications of the analytic hierarchy process. *Management science,* 26 (7), 641-658.

Yoe, Charles (2011). *Principles of risk analysis: decision making under uncertainty.* CRC press.

Zaim, Selim, et al. (2012). Maintenance strategy selection using AHP and ANP algorithms: a case study. *Journal of quality in maintenance engineering,* 18 (1), 16-29.

Zhang, Peng, Peng, Xingyu and LI, Xinqian (2007). Oil and Gas Pipeline Limited Charge Optimum Maintenance Decision-Making Analysis Based on Fuzzy-Gray-Element Theory and Fuzzy Analytical Hierarchy Process*. In: *Fuzzy Information and Engineering.* Springer, 455-463.

Zohrul Kabir, Abm and Al-Olayan, Ahmed S. (1994). Joint optimization of age replacement and continuous review spare provisioning policy. *International journal of operations & production management,* 14 (7), 53-69.

Appendices

This section provides other important parts of the research, and consists of four appendices. Appendix (A) shows the questionnaire that used for the verification of the proposed hierarchy structure for the selection of maintenance policy. Appendix (B) provides the questionnaire for the pairwise comparison. Appendix (C) demonstrates the total maintenance cost for the major services. Appendix (D) captures the weekly movement of part (1) under the proposed integrated approach.

Appendix (A): A Questionnaire for Validating the Proposed Strategic

The hierarchy structure for the selection of the maintenance policy within the petroleum industry

As an important part of our research to develop a framework for strategic purpose of maintenance management in oil and gas industry to optimise the maintenance's activities by selecting the most appropriate maintenance policy(s) to equipment in the oil and gas field. We have created a model as shown in page (8) using analytic hierarchy process (AHP) and we have identified the criteria and sub-criteria for the main target "Maintenance optimum policy". As an experienced engineer/manager in this field we are seeking your assistance to help us completing the work successfully. Your contribution and participation is highly appreciated and we would like to thank you in advance for your time and answers.

Your information and answers will be kept confidential.

Please complete the following information and return it together with the completed questionnaire;

Name: (optional):-

Field of expertise:-

Years of experience:-

Tel No:-

E-mail:-

Criteria and sub criteria

Maintenance as multi criteria decision making has different criteria and sub criteria which affect and shape up the final selected strategy(s) of maintenance when using analytic hierarchy process (AHP). Different levels of criteria, sub-criteria and alternatives are modelled to comprehensively consider achieving the main target of maintenance management in the oil and gas fields. We have identified and modelled four levels of our hierarchy framework. Please consider each of these four levels and make your comments and suggestions in the boxes below each of the levels.

Level (1)

In the first level, we have identified four main criteria namely" safety, cost, availability, reliability" that have a direct impact on the main target of maintenance "Optimum maintenance policy".

Safety: - Safety level in the oil and gas industry is high, due to the possibility of the risk of the failure and its catastrophic consequences and damages.

Reliability: - reliability is another main parameter that comes into account when planning and managing asset's maintenance in the oil and gas industry. Reliability in general is function of time, so predefined reliable system is a system that works as expected within a given time.

Availability: -The degree to a piece of equipment works properly when it is required and computed as uptime divided by both uptime plus downtime. The criticality of availability of the asset is a main factor when planning maintenance

Cost: - The costs incurred to keep an item in good condition and/or good working order is a main criterion that influences the maintenance management decision on the policy that will be associated with the machines.

Please state that if you agree on these four criteria being the most direct influence on the main target. If you have any comments on or addition factor that you would like to suggest in regard to level (1) please state that in following box.

Level (2)

The main criteria in level 1 have other sub criteria that influence each of them. We have identified them and listed all sub criteria that have an impact on the upper level of main criteria.

Safety: - four sub criteria that are considered when evaluating the safety.

The likelihood of failure: - indicating to the possibility of the occurrence of risk as a consequence of the failure.

Personals:- Considering the consequences of the failure on personals

Facility:- This sub-criterion considers the impact of the failure on the machine itself or consequentially on other machines.

Environments:- The consequences of the failure of equipment on the environment.

State that if you agree on these 2 criteria being the only influence on safety and if you disagree or have additional concerns, please show them in the box below.

Reliability: - has been identified to have three sub criteria that have direct influence that are:-

Maintenance significant items (MSI): - it is the factor that when the maintenance management decided on the importance of the equipment to the reliability of the system and if the machine would lead to shut down and disturb the process.

Mean time between failure (MTBF):- Considers the average time between failure for equipment.

Accessible to Inspection: - accessibility to machines and the easier to be inspected the more reliable the machine becomes and the more data and information is available the more understanding of the machine's condition becomes.

State that if you agree on these 2 criteria being the only influence on reliability and if you disagree or have additional concerns, please show them in the box below.

Availability: - has been identified to have three sub criteria that have direct influence on it which are:-

Main time to repair (MTTR): - it is the time needed to repair or recover the system from the failure. MTTR includes the time to diagnose the problem, the time to get the technicians and material needed on site and the time it takes to physically repair the system.

Inherent availability :- Inherent availability considers the availability of the equipment and its importance and criticality to the system that might lead to putting the system down in case of failure. The equipment is considered to be inherent to the system when, for instance, it has no stand-by equipment.

Availability on demand :- In this case, the availability of equipment is on demand. For example, it has spare system that can take over in case of maintenance or failure.

State that if you agree on these sub-criteria being the only influence on availability and if you disagree or have additional concerns, please show them in the box below.

Cost: - there are five different costs that have been identified to impact on the cost in level 1 and they are: -

Manpower: - The number of technicians needed in each type of maintenance and acceptable qualifications they have.

Spare parts: - the cost of the spare parts should be considered as the cost of them will affect the selected maintenance policy.

Production loss: - The loss of producing the crude while performing each type of maintenance policy.

E-maintenance: - It indicates to the cost of the hardware "computers and sensors" and the cost of the software which is needed for analysing measured parameters data when using condition- based maintenance.

Production damage: - it indicates to the possibility of damaging the production due to the failure.

State that if you agree on these sub-criteria being the only influence on the cost and if you disagree or have additional concerns, please show them in the box below.

Level 4

Three alternative maintenance policies have been identified as possible policies to select for proposed model:-

Planed corrective maintenance (CM): - it is the type of maintenance when the machine is run to failure after the maintenance management has decided that the failure cannot disturb the productivity and it can be repaired quickly.

Time based maintenance (TBM): - it is planned and performed periodically "calendar time, operating time or age" to reduce frequent and sudden failure.

Condition based maintenance (CBM): - The decision is made depending on the measured data. Techniques such as vibration monitoring, lubricating analysis, and ultrasonic testing are used to tell engineers whether the situation is normal or allowing the maintenance staff to implement necessary maintenance before failure occurs.

State that if you agree on these alternatives being used in oil and gas field as maintenance policies and if you disagree or have additional concerns, please show them in the box below.

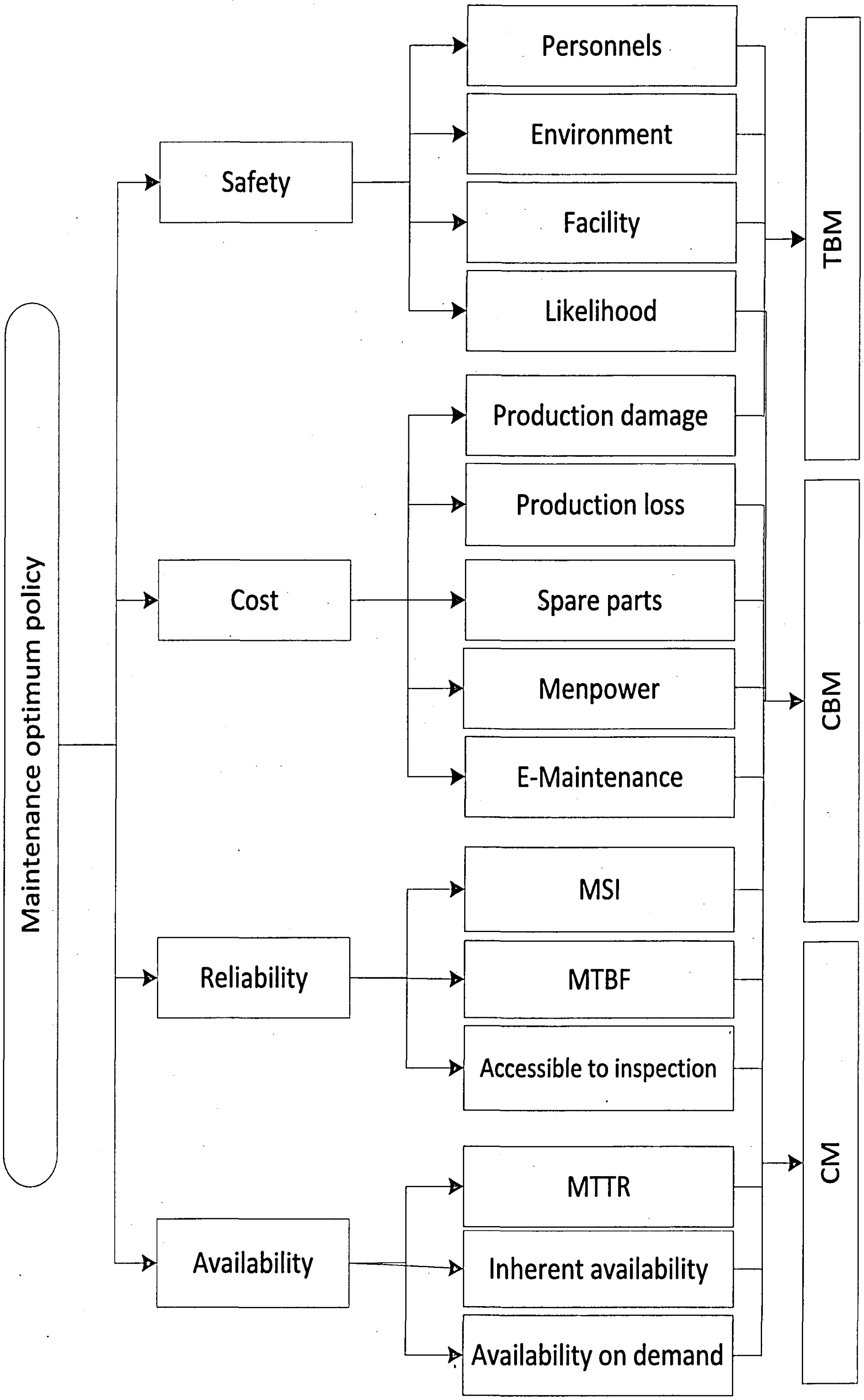


Figure A-1: The proposed model of the strategic level in oil and gas field

If you have any more concerns and adjustment to the model, we would be pleased to read about it. Please wirte them in the box below.

Appendix (B):-Maintenance Strategy Selection for Petroleum Equipment

As an important part of our research to develop a framework for selecting the most appropriate maintenance policy to equipment in the oil and gas field, we implemented Analytic Hierarchy Process (AHP). we have identify the criteria, sub-criteria and alternatives as shown in figure(B-1) to meet the main target "optimum maintenance policy". As an experienced engineer/manager in this field we are seeking your assistance to help us completing this survey. This survey is for selecting the maintenance policy for separators within the production line in the oil and gas field "the separator function is to separate oil and water as first treatment which is so important to the production line ". Each question is to compare between two elements with respect the higher connected level and you have to select one answer by clicking on the answer to emphasise to what extend you think one element is either more, less or equally important to another element.

Your contribution and participation is highly appreciated and we would like to thank you in advance for your time and answers.

The questionnaire was created by google doc and sent out on the form of a link which is attached bellow:-

https://docs.google.com/forms/d/1Mj1kSaGQjjhb8_J34qS0fkkYiDCounBM-3XH1g6JQCw/viewform

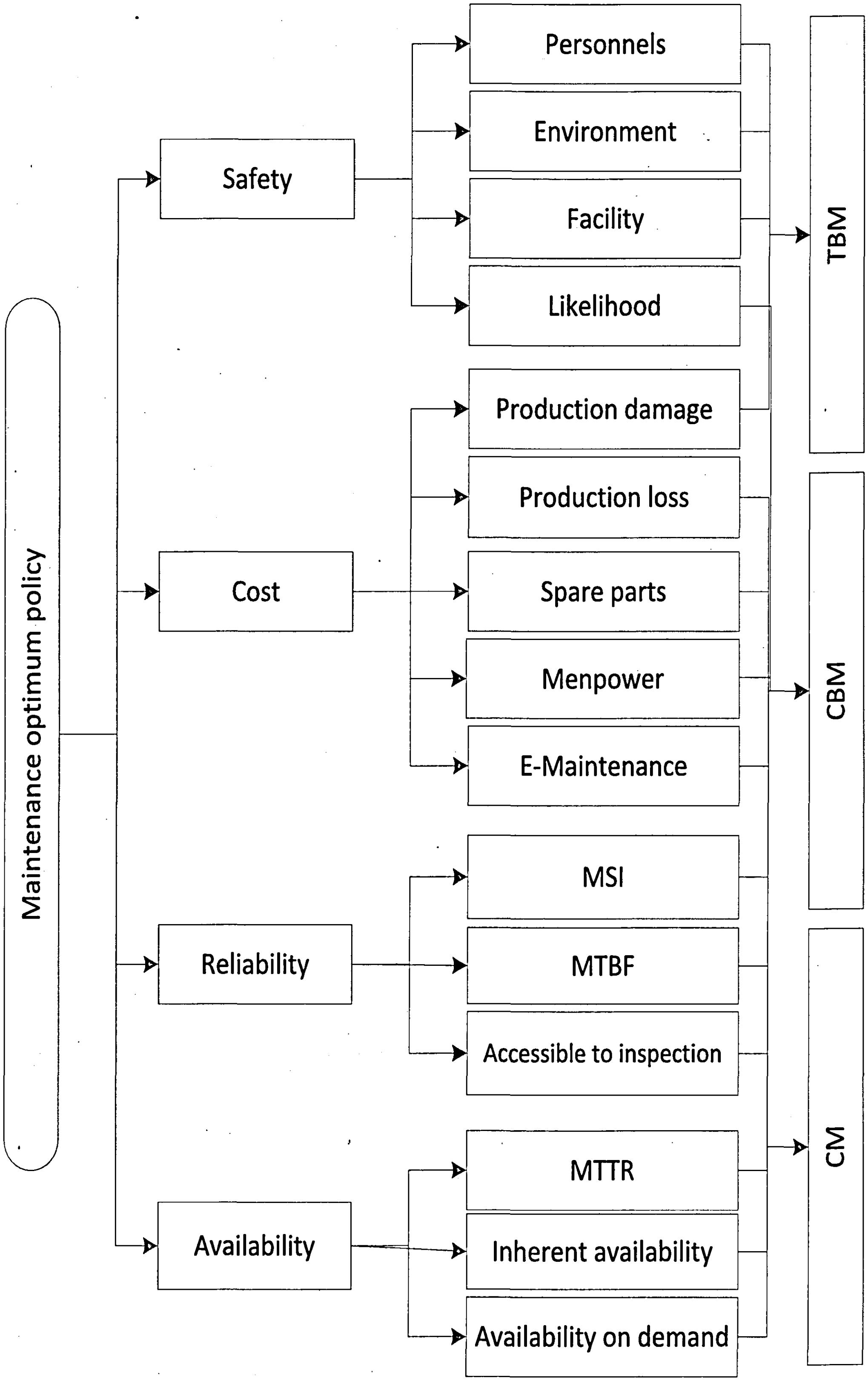


Figure (B-1): Proposed hierarchy structure for the selection of maintenance's policy

Participant name:-

Occupation:-

Years of experience:-

Sector Of experience:-

Academic:-

Industrial:-

Both:-

Others:-

1 Comparison between the main criteria" cost, reliability, availability and safety is performed with respect to the main target "Optimum maintenance selection"

Compare the relative importance between COST and RELIABILITY with respect to the main target "optimum maintenance policy"

Reliability means the importance of equipment to the reliability of production line to be function as expected. Cost includes costs that associated with the maintenance activities such as spare parts, men power, production damage and production loss in terms of failure

- 9 Cost is extremely more important than reliability
- 7 Cost is very strongly more important than reliability
- 5 Cost is strongly more important than reliability
- 3 Cost is moderately more important than reliability
- 1 Cost and reliability are equally important
- 3 Reliability is moderately more important than cost
- 5 Reliability is strongly more important than cost
- 7 Reliability is very strongly more important than cost
- 9 Reliability is extremely more important than cost

Compare the relative importance between SAFETY and RELIABILITY with respect to the main target "optimum maintenance policy"

Safety concerns with the likelihood and consequences of the failure. Reliability means the importance of equipment to the reliability of production line to be function as expected

- 9 Safety is extremely important than reliability
- 7 Safety is very strongly more important than reliability
- 5 Safety is strongly more important than reliability
- 3 Safety is moderately more important than reliability
- 1 Safety and reliability are equally important
- 3 Reliability is moderately more important than safety
- 5 Reliability is strongly more important than safety
- 7 Reliability is very strongly more important than safety
- 9 Reliability is extremely more important than safety

Compare the relative importance between SAFETY and COST with respect to the main target "optimum maintenance policy"

Safety concerns with the likelihood and consequences of the failure. Cost includes costs that associated with the maintenance activities such as spare parts, men power, production damage and production loss in terms of failure

- 9 Safety is extremely more important than cost
- 7 Safety is very strongly more important than cost
- 5 Safety is strongly more important than cost

- 3 Safety is moderately more important than cost
- 1 Safety and cost are equally important
- 3 Cost is moderately more important than safety
- 5 Cost is strongly more important than safety
- 7 Cost is very strongly more important than safety
- 9 Cost is extremely more important than safety

Compare the relative importance between AVAILABILITY and RELIABILITY with respect to the main target "optimum maintenance policy"

Reliability means the importance of equipment to the reliability of production line to be function as expected. Availability means how important the equipment to be available for the production line.

- 9 Availability is extremely more important than reliability
- 7 Availability is very strongly more important than reliability
- 5 Availability is strongly more important than reliability
- 3 Availability is moderately more important than reliability
- 1 Availability and reliability are equally important
- 3 Reliability is moderately more important than availability
- 5 Reliability is strongly more important than availability
- 7 Reliability is very strongly more important than availability
- 9 Reliability is extremely more important than availability

Compare the relative importance between AVAILABILITY and COST with respect to the main target "optimum maintenance policy"

Cost includes costs that associated with the maintenance activities such as spare parts, men power, production damage and production loss in terms of failure. Availability means how important the equipment to be available for the production line.

- 9 Availability is extremely more important than cost
- 7 Availability is very strongly more important than cost
- 5 Availability is strongly more important than cost
- 3 Availability is moderately more important than cost
- 1 Availability and cost are equally important
- 3 Cost is moderately more important than availability
- 5 Cost is strongly more important than availability
- 7 Cost is very strongly more important than availability
- 9 Cost is extremely more important than availability

Compare the relative importance between AVAILABILITY and SAFETY with respect to the main target "optimum maintenance policy"

Safety concerns with the likelihood and consequences of the failure. Availability means how important the equipment to be available for the production line.

- 9 Availability is extremely more important than safety
- 7 Availability is very strongly more important than safety
- 5 Availability is strongly more important than safety
- 3 Availability is moderately more important than safety
- 1 Availability and safety are equally important
- 3 Safety is moderately more important than availability
- 5 Safety is strongly more important than availability
- 7 Safety is very strongly more important than availability
- 9 Safety is extremely more important than availability

2 Comparison between the associated sub criteria of cost with respect to cost

Compare the relative importance between PRODUCTION DAMAGE and PRODUCTION LOSS with respect to Cost

Production damage indicates to cost of the damaged production in case of failure. Production Loss indicates to the production that is not being produced because of the failure

- 9 Production damage is extremely more important than production loss
- 7 Production damage is very strongly more important than production loss
- 5 Production damage is strongly more important than production loss
- 3 Production damage is moderately more important than production loss
- 1 Production damage and production loss are equally important
- 3 Production loss is moderately more important than production damage
- 5 Production loss is strongly more important than production damage
- 7 Production loss is very strongly more important than production damage
- 9 Production loss is extremely more important than production damage

Compare the relative importance between PRODUCTION DAMAGE and SPARE-PARTS with respect to Cost

Production damage indicates to cost of the damaged production in case of failure. Spare-parts indicate to the cost of spare-parts.

- 9 Production damage is extremely more important than spare-parts
- 7 Production damage is very strongly more important than spare-parts
- 5 Production damage is strongly more important than spare-parts
- 3 Production damage is moderately more important than production loss
- 1 Production damage and spare-parts are equally important

- ○ 3 Spare-parts is moderately more important than Production damage
- ○ 5 Spare-parts is strongly more important than Production damage
- ○ 7 Spare-parts is very strongly more important than Production damage
- ○ 9 Spare-parts is extremely more important than Production damage

Compare the relative importance between PRODUCTION-DAMAGE and MEN-POWER with respect to Cost

Production damage indicates to cost of the damaged production in case of failure. Men-power indicates to cost of the men-power in terms of salaries and quantity

- ○ 9 Production damage is extremely more important than men-power
- ○ 7 Production damage is very strongly more important than men-power
- ○ 5 Production damage is strongly more important than men-power
- ○ 3 Production damage is moderately more important than men-power
- ○ 1 Production damage and men-power are equally important
- ○ 3 Men-power is moderately more important than Production damage
- ○ 5 Men-power is strongly more important than Production damage
- ○ 7 Men-power is very strongly more important than Production damage
- ○ 9 Men-power is extremely more important than Production damage

Compare the relative importance between PRODUCTION-DAMAGE and E-MAINTENANCE with respect to Cost

Production damage indicates to cost of the damaged production in case of failure. E-maintenance indicates to the associated costs of software and hardware needed monitor the equipment

- ○ 9 Production damage is extremely more important than E-maintenance
- ○ 7 Production damage is very strongly more important than E-maintenance
- ○ 5 Production damage is strongly more important than E-maintenance
- ○ 3 Production damage is moderately more important than E-maintenance
- ○ 1 Production damage and E-maintenance are equally important
- ○ 3 E-maintenance is moderately more important than Production damage
- ○ 5 E-maintenance is strongly more important than Production damage
- ○ 7 E-maintenance is very strongly more important than Production damage
- ○ 9 E-maintenance is extremely more important than Production damage

Compare the relative importance between PRODUCTION-LOSS and MEN-POWER with respect to Cost

Production Loss indicates to the production that is not being produced because of the failure. Men-power indicates to cost of the men-power in terms of salaries and quantity

- ○ 9 Production loss is extremely more important than men-power
- ○ 7 Production loss is very strongly more important than men-power

- 5 Production loss is strongly more important than men-power
- 3 Production loss is moderately more important than men-power
- 1 Production loss and men-power are equally important
- 3 Men-power is moderately more important than production loss
- 5 Men-power is strongly more important than production loss
- 7 Men-power is very strongly more important than production loss
- 9 Men-power is extremely more important than production loss

Compare the relative importance between PRODUCTION-LOSS and E-MAINTENANCE with respect to Cost

Production Loss indicates to the production that is not being produced because of the failure. E-maintenance indicates to the associated costs of software and hardware needed monitor the equipment

- 9 Production loss is extremely more important than E-maintenance
- 7 Production loss is very strongly more important than E-maintenance
- 5 Production loss is strongly more important than E-maintenance
- 3 Production loss is moderately more important than E-maintenance
- 1 Production loss and E-maintenance are equally important
- 3 E-maintenance is moderately more important than production loss
- 5 E-maintenance is strongly more important than production loss
- 7 E-maintenance is very strongly more important than production loss
- 9 E-maintenance is extremely more important than production loss

Compare the relative importance between PRODUCTION-LOSS and SPARE-PARTS with respect to Cost

Production Loss indicates to the production that is not being produced because of the failure. Spare-parts indicate to the cost of spare-parts.

- 9 Production loss is extremely more important than spare-parts
- 7 Production loss is very strongly more important than spare-parts
- 5 Production loss is strongly more important than spare-parts
- 3 Production loss is moderately more important than spare-parts
- 1 Production loss and spare-parts are equally important
- 3 Spare-parts is moderately more important than production loss
- 5 Spare-parts is strongly more important than production loss
- 7 Spare-parts is very strongly more important than production loss
- 9 Spare-parts is extremely more important than production loss

Compare the relative importance between SPARE-PARTS and MEN-POWER with respect to Cost

Men-power indicates to cost of the men-power in terms of salaries and quantity . Spare-parts indicate to the cost of spare-parts.

- 9 Men-power is extremely more important than spare-parts
- 7 Men-power is very strongly more important than spare-parts
- 5 Men-power is strongly more important than spare-parts
- 3 Men-power is moderately more important than spare-parts
- 1 Men-power and spare-parts are equally important
- 3 Spare-parts is moderately more important than men-power
- 5 Spare-parts is strongly more important than men-power
- 7 Spare-parts is very strongly more important than men-power
- 9 Spare-parts is extremely more important than men-power

Compare the relative importance between SPARE-PARTS and E-MAINTENANCE with respect to Cost

Spare-parts indicate to the cost of spare-parts. E-maintenance indicates to the associated costs of software and hardware needed monitor the equipment

- 9 E-maintenance is extremely more important than spare-parts
- 7 E-maintenance is very strongly more important than spare-parts
- 5 E-maintenance is strongly more important than spare-parts
- 3 E-maintenance is moderately more important than spare-parts
- 1 E-maintenance and spare-parts are equally important
- 3 Spare-parts is moderately more important than E-maintenance
- 5 Spare-parts is strongly more important than E-maintenance
- 7 Spare-parts is very strongly more important than E-maintenance
- 9 Spare-parts is extremely more important than E-maintenance

Compare the relative importance between MEN-POWER and E-MAINTENANCE with respect to Cost

Men-power indicates to cost of the men-power in terms of salaries and quantity . E-maintenance indicates to the associated costs of software and hardware needed monitor the equipment

- 9 E-maintenance is extremely more important than Men-power
- 7 E-maintenance is very strongly more important than Men-power
- 5 E-maintenance is strongly more important than Men-power
- 3 E-maintenance is moderately more important than Men-power
- 1 E-maintenance and Men-power are equally important
- 3 Men-power is moderately more important than E-maintenance
- 5 Men-power is strongly more important than E-maintenance
- 7 Men-power is very strongly more important than E-maintenance

- 9 Men-power is extremely more important than E-maintenance

3 Comparison between the associated sub-criteria of reliability with respect to reliability

Compare the relative importance between MAINTENANCE SIGNIFICANT ITEMS and ACCESSIBLE TO INSPECTION with respect to RELIABILITY

Maintenance significant items means the importance of the equipment to the production line and to the reliability of the system. Accessible to inspection indicates to how accessible the equipment to be inspected to increase the confidence level of the system

- 9 Maintenance significant items is extremely more important than accessible to inspection
- 7 Maintenance significant items is very strongly more important than accessible to inspection
- 5 Maintenance significant items is strongly more important than accessible to inspection
- 3 Maintenance significant items is moderately more important than accessible to inspection
- 1 Maintenance significant items and accessible to inspection are equally important
- 3 Accessible to inspection is moderately more important than maintenance significant items
- 5 Accessible to inspection is strongly more important than maintenance significant items
- 7 Accessible to inspection is very strongly more important than maintenance significant items
- 9 Accessible to inspection is extremely more important than maintenance significant items

Compare the relative importance between MAINTENANCE SIGNIFICANT ITEMS and MEAN TIME BETWEEN FAILURE (MTBF) with respect to RELIABILITY

Maintenance significant items means the importance of the equipment to the production line and to the reliability of the system. MTBF indicates to the period of time between failures and the longer the time the more reliable the equipment

- 9 Maintenance significant items is extremely more important than MTBF
- 7 Maintenance significant items is very strongly more important than MTBF
- 5 Maintenance significant items is strongly more important than MTBF
- 3 Maintenance significant items is moderately more important than MTBF
- 1 Maintenance significant items and MTBF are equally important
- 3 MTBF is moderately more important than maintenance significant items

- 5 MTBF is strongly more important than maintenance significant items
- 7 MTBF is very strongly more important than maintenance significant items
- 9 MTBF is extremely more important than maintenance significant items

Compare the relative importance between ACCESSIBLE TO INSPECTION and MEAN TIME BETWEEN FAILURE (MTBF) with respect to RELIABILITY

Accessible to inspection indicates to how accessible the equipment to be inspected to increase the confidence level of the system . MTBF indicates to the period of time between failures and the longer the time the more reliable the equipment

- 9 Accessible to inspection is extremely more important than MTBF
- 7 Accessible to inspection is very strongly more important than MTBF
- 5 Accessible to inspection is strongly more important than MTBF
- 3 Accessible to inspection is moderately more important than MTBF
- 1 Accessible to inspection and MTBF are equally important
- 3 MTBF is moderately more important than Accessible to inspection
- 5 MTBF is strongly more important than Accessible to inspection
- 7 MTBF is very strongly more important than Accessible to inspection
- 9 MTBF is extremely more important than Accessible to inspection

4 Comparison between the associated sub-criteria of safety with respect to safety

Compare the relative importance between LIKELIHOOD and FACILITY with respect to SAFTEY

Likelihood indicates to the possibility of the occurrence of the risk in terms of failure. Facility indicates to the consequences of the failure on damaging the facility

- 9 Likelihood is extremely more important than facility
- 7 Likelihood is very strongly more important than facility
- 5 Likelihood is strongly more important than facility
- 3 Likelihood is moderately more important than facility
- 1 Likelihood and facility are equally important
- 3 Facility is moderately more important than likelihood
- 5 Facility is strongly more important than likelihood
- 7 Facility is very strongly more important than likelihood
- 9 Facility is extremely more important than likelihood

Compare the relative importance between LIKELIHOOD and PERSONNELS with respect to SAFTEY

Likelihood indicates to the possibility of the occurrence of the risk in terms of failure. Personnels indicates to the consequences of the failure on any person who would be around if failure happened

- 9 Likelihood is extremely more important than personnels
- 7 Likelihood is very strongly more important than personnels
- 5 Likelihood is strongly more important than personnels
- 3 Likelihood is moderately more important than personnels
- 1 Likelihood and personnels are equally important
- 3 Personnels is moderately more important than likelihood
- 5 Personnels is strongly more important than likelihood
- 7 Personnels is very strongly more important than likelihood
- 9 Personnels is extremely more important than likelihood

Compare the relative importance between LIKELIHOOD and ENVIRONMENT with respect to SAFTEY

Likelihood indicates to the possibility of the occurrence of the risk in terms of failure. Environment indicates to the consequences of the failure on the surroundings and the effect of the failure on the environment

- 9 Likelihood is extremely more important than environment
- 7 Likelihood is very strongly more important than environment
- 5 Likelihood is strongly more important than environment
- 3 Likelihood is moderately more important than environment
- 1 Likelihood and environment are equally important
- 3 Environment is moderately more important than likelihood
- 5 Environment is strongly more important than likelihood
- 7 Environment is very strongly more important than likelihood
- 9 Environment is extremely more important than likelihood

Compare the relative importance between PERSONNELS and ENVIRONMENT with respect to SAFTEY

Personnels indicates to the consequences of the failure on any person who would be around if failure happened. Environment indicates to the consequences of the failure on the surroundings and the effect of the failure on the environment

- 9 Personnels is extremely more important than environment
- 7 Personnels is very strongly more important than environment
- 5 Personnels is strongly more important than environment
- 3 Personnels is moderately more important than environment
- 1 Personnels and environment are equally important
- 3 Environment is moderately more important than personnels
- 5 Environment is strongly more important than personnels
- 7 Environment is very strongly more important than personnels
- 9 Environment is extremely more important than personnels

Compare the relative importance between FACILITY and ENVIRONMENT with respect to SAFTEY

Facility indicates to the consequences of the failure on damaging the facility. Environment indicates to the consequences of the failure on the surroundings and the effect of the failure on the environment

- 9 Facility is extremely more important than environment
- 7 Facility is very strongly more important than environment
- 5 Facility is strongly more important than environment
- 3 Facility is moderately more important than environment
- 1 Facility and environment are equally important
- 3 Environment is moderately more important than facility
- 5 Environment is strongly more important than facility
- 7 Environment is very strongly more important than facility
- 9 Environment is extremely more important than facility

Compare the relative importance between PERSONNELS and FACILITY with respect to SAFTEY

Personnels indicates to the consequences of the failure on any person who would be around if failure happened. Environment indicates to the consequences of the failure on the surroundings and the effect of the failure on the environment

- 9 Personnels is extremely more important than facility
- 7 Personnels is very strongly more important than facility
- 5 Personnels is strongly more important than facility
- 3 Personnels is moderately more important than facility
- 1 Personnels and facility are equally important
- 3 Facility is moderately more important than personnels
- 5 Facility is strongly more important than personnels
- 7 Facility is very strongly more important than personnels
- 9 Facility is extremely more important than personnels

5 Comparison between the associated sub-criteria of availability with respect to availability

Compare the relative importance between AVAILABILITY ON DEMAND and INHERENT AVAILABILITY with respect to AVAILABILITY

Availability on demand indicates to that equipment is either has alternative equipment that to swap with or not required to be working all the time for the system to be functioning. Inherent availability indicates to that the equipment is always required to be working for the production line to be functioning

- 9 Availability on demand is extremely more important than inherent availability

- 7 Availability on demand is very strongly more important than inherent availability
- 5 Availability on demand is strongly more important than inherent availability
- 3 Availability on demand is moderately more important than inherent availability
- 1 Availability on demand and inherent availability are equally important
- 3 Inherent availability is moderately more important than Availability on demand
- 5 Inherent availability is strongly more important than Availability on demand
- 7 Inherent availability is very strongly more important than Availability on demand
- 9 Inherent availability is extremely more important than Availability on demand

Compare the relative importance between AVAILABILITY ON DEMAND and MEAN TIME TO REPAIR (MTTR) with respect to AVAILABILITY

Availability on demand indicates to that equipment is either has alternative equipment that to swap with or not required to be working all the time for the system to be functioning. MTTR represents the average (mean) time required to repair a failed component or equipment

- 9 Availability on demand is extremely more important than MTTR
- 7 Availability on demand is very strongly more important than MTTR
- 5 Availability on demand is strongly more important than MTTR
- 3 Availability on demand is moderately more important than MTTR
- 1 Availability on demand and MTTR are equally important
- 3 MTTR is moderately more important than Availability on demand
- 5 MTTR is strongly more important than Availability on demand
- 7 MTTR is very strongly more important than Availability on demand
- 9 MTTR is extremely more important than Availability on demand

Compare the relative importance between INHERENT AVAILABILITY and MEAN TIME TO REPAIR (MTTR) with respect to AVAILABILITY

Inherent availability indicates to that the equipment is always required to be working for the production line to be functioning. MTTR represents the average (mean) time required to repair a failed component or equipment

- 9 Inherent availability is extremely more important than MTTR
- 7 Inherent availability is very strongly more important than MTTR
- 5 Inherent availability is strongly more important than MTTR
- 3 Inherent availability is moderately more important than MTTR

- 1 Inherent availability and MTTR are equally important
- 3 MTTR is moderately more important than inherent availability
- 5 MTTR is strongly more important than inherent availability
- 7 MTTR is very strongly more important than inherent availability
- 9 MTTR is extremely more important than inherent availability

Comparison between the alternatives "time based maintenance, condition based maintenance and corrective maintenance" with respect to each one of the sub-criteria

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and TIME BASED MAINTENANCE (TBM) with respect to personnels/safety

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you run the equipment until it fails. Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine".

- 9 Corrective maintenance is extremely more important than time based maintenance
- 7 Corrective maintenance is very strongly more important than time based maintenance
- 5 Corrective maintenance is strongly more important than time based maintenance
- 3 Corrective maintenance is moderately more important than time based maintenance
- 1 Corrective maintenance and time based maintenance are equally important
- 3 Time based maintenance is moderately more important than corrective maintenance
- 5 Time based maintenance is strongly more important than corrective maintenance
- 7 Time based maintenance is very strongly more important than corrective maintenance
- 9 Time based maintenance is extremely more important than corrective maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and CONDITION BASED MAINTENANCE (CBM) with respect to Personnels/safety

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you the equipment is run until it fails. Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Corrective maintenance is extremely more important than condition based maintenance
- 7 Corrective maintenance is very strongly more important than condition based maintenance
- 5 Corrective maintenance is strongly more important than condition based maintenance
- 3 Corrective maintenance is moderately more important than condition based maintenance
- 1 Corrective maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than corrective maintenance
- 5 Condition based maintenance is strongly more important than corrective maintenance
- 7 Condition based maintenance is very strongly more important than corrective maintenance
- 9 Condition based maintenance is extremely more important than corrective maintenance

Compare the relative importance between TIME BASED MAINTENANCE (TBM) and CONDITION BASED MAINTENANCE (CBM) with respect to personnels/safety

"Please provide your judgement with respect to this particular sub-criterion". Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine". Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Time based maintenance is extremely more important than condition based maintenance
- 7 Time based maintenance is very strongly more important than condition based maintenance
- 5 Time based maintenance is strongly more important than condition based maintenance
- 3 Time based maintenance is moderately more important than condition based maintenance
- 1 Time based maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than time based maintenance
- 5 Condition based maintenance is strongly more important than time based maintenance

- 7 Condition based maintenance is very strongly more important than time based maintenance
- 9 Condition based maintenance is extremely more important than time based maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and TIME BASED MAINTENANCE (TBM) with respect to Environment/safety

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you run the equipment until it fails. Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine".

- 9 Corrective maintenance is extremely more important than time based maintenance
- 7 Corrective maintenance is very strongly more important than time based maintenance
- 5 Corrective maintenance is strongly more important than time based maintenance
- 3 Corrective maintenance is moderately more important than time based maintenance
- 1 Corrective maintenance and time based maintenance are equally important
- 3 Time based maintenance is moderately more important than corrective maintenance
- 5 Time based maintenance is strongly more important than corrective maintenance
- 7 Time based maintenance is very strongly more important than corrective maintenance
- 9 Time based maintenance is extremely more important than corrective maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and CONDITION BASED MAINTENANCE (CBM) with respect to Environment/safety

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you the equipment is run until it fails. Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Corrective maintenance is extremely more important than condition based maintenance
- 7 Corrective maintenance is very strongly more important than condition based maintenance
- 5 Corrective maintenance is strongly more important than condition based maintenance

- 3 Corrective maintenance is moderately more important than condition based maintenance
- 1 Corrective maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than corrective maintenance
- 5 Condition based maintenance is strongly more important than corrective maintenance
- 7 Condition based maintenance is very strongly more important than corrective maintenance
- 9 Condition based maintenance is extremely more important than corrective maintenance

Compare the relative importance between TIME BASED MAINTENANCE (TBM) and CONDITION BASED MAINTENANCE (CBM) with respect to Environment/safety

"Please provide your judgement with respect to this particular sub-criterion". Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine". Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Time based maintenance is extremely more important than condition based maintenance
- 7 Time based maintenance is very strongly more important than condition based maintenance
- 5 Time based maintenance is strongly more important than condition based maintenance
- 3 Time based maintenance is moderately more important than condition based maintenance
- 1 Time based maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than time based maintenance
- 5 Condition based maintenance is strongly more important than time based maintenance
- 7 Condition based maintenance is very strongly more important than time based maintenance
- 9 Condition based maintenance is extremely more important than time based maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and TIME BASED MAINTENANCE (TBM) with respect to Facility/Safety

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you run the equipment until it fails. Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine".

- 9 Corrective maintenance is extremely more important than time based maintenance
- 7 Corrective maintenance is very strongly more important than time based maintenance
- 5 Corrective maintenance is strongly more important than time based maintenance
- 3 Corrective maintenance is moderately more important than time based maintenance
- 1 Corrective maintenance and time based maintenance are equally important
- 3 Time based maintenance is moderately more important than corrective maintenance
- 5 Time based maintenance is strongly more important than corrective maintenance
- 7 Time based maintenance is very strongly more important than corrective maintenance
- 9 Time based maintenance is extremely more important than corrective maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and CONDITION BASED MAINTENANCE (CBM) with respect to Facility/safety

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you the equipment is run until it fails. Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Corrective maintenance is extremely more important than condition based maintenance
- 7 Corrective maintenance is very strongly more important than condition based maintenance
- 5 Corrective maintenance is strongly more important than condition based maintenance
- 3 Corrective maintenance is moderately more important than condition based maintenance
- 1 Corrective maintenance and condition based maintenance are equally important

- 3 Condition based maintenance is moderately more important than corrective maintenance
- 5 Condition based maintenance is strongly more important than corrective maintenance
- 7 Condition based maintenance is very strongly more important than corrective maintenance
- 9 Condition based maintenance is extremely more important than corrective maintenance

Compare the relative importance between TIME BASED MAINTENANCE (TBM) and CONDITION BASED MAINTENANCE (CBM) with respect to Facility/safety

"Please provide your judgement with respect to this particular sub-criterion". Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine". Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Time based maintenance is extremely more important than condition based maintenance
- 7 Time based maintenance is very strongly more important than condition based maintenance
- 5 Time based maintenance is strongly more important than condition based maintenance
- 3 Time based maintenance is moderately more important than condition based maintenance
- 1 Time based maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than time based maintenance
- 5 Condition based maintenance is strongly more important than time based maintenance
- 7 Condition based maintenance is very strongly more important than time based maintenance
- 9 Condition based maintenance is extremely more important than time based maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and TIME BASED MAINTENANCE (TBM) with respect to Likelihood/Safety

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you run the equipment until it fails. Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine".

- 9 Corrective maintenance is extremely more important than time based maintenance
- 7 Corrective maintenance is very strongly more important than time based maintenance
- 5 Corrective maintenance is strongly more important than time based maintenance
- 3 Corrective maintenance is moderately more important than time based maintenance
- 1 Corrective maintenance and time based maintenance are equally important
- 3 Time based maintenance is moderately more important than corrective maintenance
- 5 Time based maintenance is strongly more important than corrective maintenance
- 7 Time based maintenance is very strongly more important than corrective maintenance
- 9 Time based maintenance is extremely more important than corrective maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and CONDITION BASED MAINTENANCE (CBM) with respect to Likelihood/safety

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you the equipment is run until it fails. Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Corrective maintenance is extremely more important than condition based maintenance
- 7 Corrective maintenance is very strongly more important than condition based maintenance
- 5 Corrective maintenance is strongly more important than condition based maintenance
- 3 Corrective maintenance is moderately more important than condition based maintenance
- 1 Corrective maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than corrective maintenance
- 5 Condition based maintenance is strongly more important than corrective maintenance

- 7 Condition based maintenance is very strongly more important than corrective maintenance
- 9 Condition based maintenance is extremely more important than corrective maintenance

Compare the relative importance between TIME BASED MAINTENANCE (TBM) and CONDITION BASED MAINTENANCE (CBM) with respect to Likelihood/safety

"Please provide your judgement with respect to this particular sub-criterion". Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine". Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Time based maintenance is extremely more important than condition based maintenance
- 7 Time based maintenance is very strongly more important than condition based maintenance
- 5 Time based maintenance is strongly more important than condition based maintenance
- 3 Time based maintenance is moderately more important than condition based maintenance
- 1 Time based maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than time based maintenance
- 5 Condition based maintenance is strongly more important than time based maintenance
- 7 Condition based maintenance is very strongly more important than time based maintenance
- 9 Condition based maintenance is extremely more important than time based maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and TIME BASED MAINTENANCE (TBM) with respect to Production-Damage/Cost

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you run the equipment until it fails. Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine".

- 9 Corrective maintenance is extremely more important than time based maintenance
- 7 Corrective maintenance is very strongly more important than time based maintenance

- 5 Corrective maintenance is strongly more important than time based maintenance
- 3 Corrective maintenance is moderately more important than time based maintenance
- 1 Corrective maintenance and time based maintenance are equally important
- 3 Time based maintenance is moderately more important than corrective maintenance
- 5 Time based maintenance is strongly more important than corrective maintenance
- 7 Time based maintenance is very strongly more important than corrective maintenance
- 9 Time based maintenance is extremely more important than corrective maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and CONDITION BASED MAINTENANCE (CBM) with respect to Production- Damage/Cost

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you the equipment is run until it fails. Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Corrective maintenance is extremely more important than condition based maintenance
- 7 Corrective maintenance is very strongly more important than condition based maintenance
- 5 Corrective maintenance is strongly more important than condition based maintenance
- 3 Corrective maintenance is moderately more important than condition based maintenance
- 1 Corrective maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than corrective maintenance
- 5 Condition based maintenance is strongly more important than corrective maintenance
- 7 Condition based maintenance is very strongly more important than corrective maintenance
- 9 Condition based maintenance is extremely more important than corrective maintenance

Compare the relative importance between TIME BASED MAINTENANCE (TBM) and CONDITION BASED MAINTENANCE (CBM) with respect to Production-Damage/Cost

"Please provide your judgement with respect to this particular sub-criterion". Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine". Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Time based maintenance is extremely more important than condition based maintenance
- 7 Time based maintenance is very strongly more important than condition based maintenance
- 5 Time based maintenance is strongly more important than condition based maintenance
- 3 Time based maintenance is moderately more important than condition based maintenance
- 1 Time based maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than time based maintenance
- 5 Condition based maintenance is strongly more important than time based maintenance
- 7 Condition based maintenance is very strongly more important than time based maintenance
- 9 Condition based maintenance is extremely more important than time based maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and TIME BASED MAINTENANCE (TBM) with respect to Production-Loss/Cost

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you run the equipment until it fails. Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine".

- 9 Corrective maintenance is extremely more important than time based maintenance
- 7 Corrective maintenance is very strongly more important than time based maintenance
- 5 Corrective maintenance is strongly more important than time based maintenance
- 3 Corrective maintenance is moderately more important than time based maintenance
- 1 Corrective maintenance and time based maintenance are equally important

- 3 Time based maintenance is moderately more important than corrective maintenance
- 5 Time based maintenance is strongly more important than corrective maintenance
- 7 Time based maintenance is very strongly more important than corrective maintenance
- 9 Time based maintenance is extremely more important than corrective maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and CONDITION BASED MAINTENANCE (CBM) with respect to Production- Loss/Cost

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you the equipment is run until it fails. Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Corrective maintenance is extremely more important than condition based maintenance
- 7 Corrective maintenance is very strongly more important than condition based maintenance
- 5 Corrective maintenance is strongly more important than condition based maintenance
- 3 Corrective maintenance is moderately more important than condition based maintenance
- 1 Corrective maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than corrective maintenance
- 5 Condition based maintenance is strongly more important than corrective maintenance
- 7 Condition based maintenance is very strongly more important than corrective maintenance
- 9 Condition based maintenance is extremely more important than corrective maintenance

Compare the relative importance between TIME BASED MAINTENANCE (TBM) and CONDITION BASED MAINTENANCE (CBM) with respect to Production-Loss/Cost

"Please provide your judgement with respect to this particular sub-criterion". Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine". Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Time based maintenance is extremely more important than condition based maintenance
- 7 Time based maintenance is very strongly more important than condition based maintenance
- 5 Time based maintenance is strongly more important than condition based maintenance
- 3 Time based maintenance is moderately more important than condition based maintenance
- 1 Time based maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than time based maintenance
- 5 Condition based maintenance is strongly more important than time based maintenance
- 7 Condition based maintenance is very strongly more important than time based maintenance
- 9 Condition based maintenance is extremely more important than time based maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and TIME BASED MAINTENANCE (TBM) with respect to Spareparts/Cost

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you run the equipment until it fails. Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine".

- 9 Corrective maintenance is extremely more important than time based maintenance
- 7 Corrective maintenance is very strongly more important than time based maintenance
- 5 Corrective maintenance is strongly more important than time based maintenance
- 3 Corrective maintenance is moderately more important than time based maintenance
- 1 Corrective maintenance and time based maintenance are equally important
- 3 Time based maintenance is moderately more important than corrective maintenance
- 5 Time based maintenance is strongly more important than corrective maintenance
- 7 Time based maintenance is very strongly more important than corrective maintenance

- 9 Time based maintenance is extremely more important than corrective maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and CONDITION BASED MAINTENANCE (CBM) with respect to Spareparts/Cost

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you the equipment is run until it fails. Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring"..

- 9 Corrective maintenance is extremely more important than condition based maintenance
- 7 Corrective maintenance is very strongly more important than condition based maintenance
- 5 Corrective maintenance is strongly more important than condition based maintenance
- 3 Corrective maintenance is moderately more important than condition based maintenance
- 1 Corrective maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than corrective maintenance
- 5 Condition based maintenance is strongly more important than corrective maintenance
- 7 Condition based maintenance is very strongly more important than corrective maintenance
- 9 Condition based maintenance is extremely more important than corrective maintenance

Compare the relative importance between TIME BASED MAINTENANCE (TBM) and CONDITION BASED MAINTENANCE (CBM) with respect to Spareparts/Cost

"Please provide your judgement with respect to this particular sub-criterion". Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine". Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Time based maintenance is extremely more important than condition based maintenance
- 7 Time based maintenance is very strongly more important than condition based maintenance
- 5 Time based maintenance is strongly more important than condition based maintenance

- 3 Time based maintenance is moderately more important than condition based maintenance
- 1 Time based maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than time based maintenance
- 5 Condition based maintenance is strongly more important than time based maintenance
- 7 Condition based maintenance is very strongly more important than time based maintenance
- 9 Condition based maintenance is extremely more important than time based maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and TIME BASED MAINTENANCE (TBM) with respect to Menpower/Cost

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you run the equipment until it fails. Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine".

- 9 Corrective maintenance is extremely more important than time based maintenance
- 7 Corrective maintenance is very strongly more important than time based maintenance
- 5 Corrective maintenance is strongly more important than time based maintenance
- 3 Corrective maintenance is moderately more important than time based maintenance
- 1 Corrective maintenance and time based maintenance are equally important
- 3 Time based maintenance is moderately more important than corrective maintenance
- 5 Time based maintenance is strongly more important than corrective maintenance
- 7 Time based maintenance is very strongly more important than corrective maintenance
- 9 Time based maintenance is extremely more important than corrective maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and CONDITION BASED MAINTENANCE (CBM) with respect to Menpower/Cost

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you the equipment is run until it fails.

Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Corrective maintenance is extremely more important than condition based maintenance
- 7 Corrective maintenance is very strongly more important than condition based maintenance
- 5 Corrective maintenance is strongly more important than condition based maintenance
- 3 Corrective maintenance is moderately more important than condition based maintenance
- 1 Corrective maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than corrective maintenance
- 5 Condition based maintenance is strongly more important than corrective maintenance
- 7 Condition based maintenance is very strongly more important than corrective maintenance
- 9 Condition based maintenance is extremely more important than corrective maintenance

Compare the relative importance between TIME BASED MAINTENANCE (TBM) and CONDITION BASED MAINTENANCE (CBM) with respect to Menpower/Cost

"Please provide your judgement with respect to this particular sub-criterion". Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine". Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Time based maintenance is extremely more important than condition based maintenance
- 7 Time based maintenance is very strongly more important than condition based maintenance
- 5 Time based maintenance is strongly more important than condition based maintenance
- 3 Time based maintenance is moderately more important than condition based maintenance
- 1 Time based maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than time based maintenance

- 5 Condition based maintenance is strongly more important than time based maintenance
- 7 Condition based maintenance is very strongly more important than time based maintenance
- 9 Condition based maintenance is extremely more important than time based maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and TIME BASED MAINTENANCE (TBM) with respect to E-maintenance/Cost

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you run the equipment until it fails. Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine".

- 9 Corrective maintenance is extremely more important than time based maintenance
- 7 Corrective maintenance is very strongly more important than time based maintenance
- 5 Corrective maintenance is strongly more important than time based maintenance
- 3 Corrective maintenance is moderately more important than time based maintenance
- 1 Corrective maintenance and time based maintenance are equally important
- 3 Time based maintenance is moderately more important than corrective maintenance
- 5 Time based maintenance is strongly more important than corrective maintenance
- 7 Time based maintenance is very strongly more important than corrective maintenance
- 9 Time based maintenance is extremely more important than corrective maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and CONDITION BASED MAINTENANCE (CBM) with respect to E-maintenance/Cost

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you the equipment is run until it fails. Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Corrective maintenance is extremely more important than condition based maintenance
- 7 Corrective maintenance is very strongly more important than condition based maintenance

- 5 Corrective maintenance is strongly more important than condition based maintenance
- 3 Corrective maintenance is moderately more important than condition based maintenance
- 1 Corrective maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than corrective maintenance
- 5 Condition based maintenance is strongly more important than corrective maintenance
- 7 Condition based maintenance is very strongly more important than corrective maintenance
- 9 Condition based maintenance is extremely more important than corrective maintenance

Compare the relative importance between TIME BASED MAINTENANCE (TBM) and CONDITION BASED MAINTENANCE (CBM) with respect to E-maintenance/Cost

"Please provide your judgement with respect to this particular sub-criterion". Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine". Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Time based maintenance is extremely more important than condition based maintenance
- 7 Time based maintenance is very strongly more important than condition based maintenance
- 5 Time based maintenance is strongly more important than condition based maintenance
- 3 Time based maintenance is moderately more important than condition based maintenance
- 1 Time based maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than time based maintenance
- 5 Condition based maintenance is strongly more important than time based maintenance
- 7 Condition based maintenance is very strongly more important than time based maintenance
- 9 Condition based maintenance is extremely more important than time based maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and TIME BASED MAINTENANCE (TBM) with respect to Maintenance Significant Items (MSI)/Reliability

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you run the equipment until it fails. Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine".

- 9 Corrective maintenance is extremely more important than time based maintenance
- 7 Corrective maintenance is very strongly more important than time based maintenance
- 5 Corrective maintenance is strongly more important than time based maintenance
- 3 Corrective maintenance is moderately more important than time based maintenance
- 1 Corrective maintenance and time based maintenance are equally important
- 3 Time based maintenance is moderately more important than corrective maintenance
- 5 Time based maintenance is strongly more important than corrective maintenance
- 7 Time based maintenance is very strongly more important than corrective maintenance
- 9 Time based maintenance is extremely more important than corrective maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and CONDITION BASED MAINTENANCE (CBM) with respect to Maintenance Significant Items (MSI)/Reliability

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you the equipment is run until it fails. Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Corrective maintenance is extremely more important than condition based maintenance
- 7 Corrective maintenance is very strongly more important than condition based maintenance
- 5 Corrective maintenance is strongly more important than condition based maintenance
- 3 Corrective maintenance is moderately more important than condition based maintenance

- 1 Corrective maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than corrective maintenance
- 5 Condition based maintenance is strongly more important than corrective maintenance
- 7 Condition based maintenance is very strongly more important than corrective maintenance
- 9 Condition based maintenance is extremely more important than corrective maintenance

Compare the relative importance between TIME BASED MAINTENANCE (TBM) and CONDITION BASED MAINTENANCE (CBM) with respect to Maintenance Significant Items (MSI)/Reliability

"Please provide your judgement with respect to this particular sub-criterion". Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine". Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Time based maintenance is extremely more important than condition based maintenance
- 7 Time based maintenance is very strongly more important than condition based maintenance
- 5 Time based maintenance is strongly more important than condition based maintenance
- 3 Time based maintenance is moderately more important than condition based maintenance
- 1 Time based maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than time based maintenance
- 5 Condition based maintenance is strongly more important than time based maintenance
- 7 Condition based maintenance is very strongly more important than time based maintenance
- 9 Condition based maintenance is extremely more important than time based maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and TIME BASED MAINTENANCE (TBM) with respect to Accessible to inspection/Reliability

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you run the equipment until it fails. Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine".

- 9 Corrective maintenance is extremely more important than time based maintenance
- 7 Corrective maintenance is very strongly more important than time based maintenance
- 5 Corrective maintenance is strongly more important than time based maintenance
- 3 Corrective maintenance is moderately more important than time based maintenance
- 1 Corrective maintenance and time based maintenance are equally important
- 3 Time based maintenance is moderately more important than corrective maintenance
- 5 Time based maintenance is strongly more important than corrective maintenance
- 7 Time based maintenance is very strongly more important than corrective maintenance
- 9 Time based maintenance is extremely more important than corrective maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and CONDITION BASED MAINTENANCE (CBM) with respect to Accessible to inspection/Reliability

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you the equipment is run until it fails. Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Corrective maintenance is extremely more important than condition based maintenance
- 7 Corrective maintenance is very strongly more important than condition based maintenance
- 5 Corrective maintenance is strongly more important than condition based maintenance
- 3 Corrective maintenance is moderately more important than condition based maintenance
- 1 Corrective maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than corrective maintenance

- 5 Condition based maintenance is strongly more important than corrective maintenance
- 7 Condition based maintenance is very strongly more important than corrective maintenance
- 9 Condition based maintenance is extremely more important than corrective maintenance

Compare the relative importance between TIME BASED MAINTENANCE (TBM) and CONDITION BASED MAINTENANCE (CBM) with respect to Accessible to inspection/Reliability

"Please provide your judgement with respect to this particular sub-criterion". Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine". Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Time based maintenance is extremely more important than condition based maintenance
- 7 Time based maintenance is very strongly more important than condition based maintenance
- 5 Time based maintenance is strongly more important than condition based maintenance
- 3 Time based maintenance is moderately more important than condition based maintenance
- 1 Time based maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than time based maintenance
- 5 Condition based maintenance is strongly more important than time based maintenance
- 7 Condition based maintenance is very strongly more important than time based maintenance
- 9 Condition based maintenance is extremely more important than time based maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and TIME BASED MAINTENANCE (TBM) with respect to Mean Time Between Failure MTBF/Reliability

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you run the equipment until it fails. Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine".

- 9 Corrective maintenance is extremely more important than time based maintenance

- 7 Corrective maintenance is very strongly more important than time based maintenance
- 5 Corrective maintenance is strongly more important than time based maintenance
- 3 Corrective maintenance is moderately more important than time based maintenance
- 1 Corrective maintenance and time based maintenance are equally important
- 3 Time based maintenance is moderately more important than corrective maintenance
- 5 Time based maintenance is strongly more important than corrective maintenance
- 7 Time based maintenance is very strongly more important than corrective maintenance
- 9 Time based maintenance is extremely more important than corrective maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and CONDITION BASED MAINTENANCE (CBM) with respect to Mean Time Between Failure MTBF/Reliability

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you the equipment is run until it fails. Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Corrective maintenance is extremely more important than condition based maintenance
- 7 Corrective maintenance is very strongly more important than condition based maintenance
- 5 Corrective maintenance is strongly more important than condition based maintenance
- 3 Corrective maintenance is moderately more important than condition based maintenance
- 1 Corrective maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than corrective maintenance
- 5 Condition based maintenance is strongly more important than corrective maintenance
- 7 Condition based maintenance is very strongly more important than corrective maintenance

- 9 Condition based maintenance is extremely more important than corrective maintenance

Compare the relative importance between TIME BASED MAINTENANCE (TBM) and CONDITION BASED MAINTENANCE (CBM) with respect to Mean Time Between Failure MTBF/Reliability

"Please provide your judgement with respect to this particular sub-criterion". Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine". Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Time based maintenance is extremely more important than condition based maintenance
- 7 Time based maintenance is very strongly more important than condition based maintenance
- 5 Time based maintenance is strongly more important than condition based maintenance
- 3 Time based maintenance is moderately more important than condition based maintenance
- 1 Time based maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than time based maintenance
- 5 Condition based maintenance is strongly more important than time based maintenance
- 7 Condition based maintenance is very strongly more important than time based maintenance
- 9 Condition based maintenance is extremely more important than time based maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and TIME BASED MAINTENANCE (TBM) with respect to Inherent availability/Availability

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you run the equipment until it fails. Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine".

- 9 Corrective maintenance is extremely more important than time based maintenance
- 7 Corrective maintenance is very strongly more important than time based maintenance
- 5 Corrective maintenance is strongly more important than time based maintenance

- 3 Corrective maintenance is moderately more important than time based maintenance
- 1 Corrective maintenance and time based maintenance are equally important
- 3 Time based maintenance is moderately more important than corrective maintenance
- 5 Time based maintenance is strongly more important than corrective maintenance
- 7 Time based maintenance is very strongly more important than corrective maintenance
- 9 Time based maintenance is extremely more important than corrective maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and CONDITION BASED MAINTENANCE (CBM) with respect to Inherent availability/Availability

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you the equipment is run until it fails. Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Corrective maintenance is extremely more important than condition based maintenance
- 7 Corrective maintenance is very strongly more important than condition based maintenance
- 5 Corrective maintenance is strongly more important than condition based maintenance
- 3 Corrective maintenance is moderately more important than condition based maintenance
- 1 Corrective maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than corrective maintenance
- 5 Condition based maintenance is strongly more important than corrective maintenance
- 7 Condition based maintenance is very strongly more important than corrective maintenance
- 9 Condition based maintenance is extremely more important than corrective maintenance

Compare the relative importance between TIME BASED MAINTENANCE (TBM) and CONDITION BASED MAINTENANCE (CBM) with respect to Inherent availability/Availability

"Please provide your judgement with respect to this particular sub-criterion". Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine". Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Time based maintenance is extremely more important than condition based maintenance
- 7 Time based maintenance is very strongly more important than condition based maintenance
- 5 Time based maintenance is strongly more important than condition based maintenance
- 3 Time based maintenance is moderately more important than condition based maintenance
- 1 Time based maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than time based maintenance
- 5 Condition based maintenance is strongly more important than time based maintenance
- 7 Condition based maintenance is very strongly more important than time based maintenance
- 9 Condition based maintenance is extremely more important than time based maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and TIME BASED MAINTENANCE (TBM) with respect to Availability on demand/Availability

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you run the equipment until it fails. Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine".

- 9 Corrective maintenance is extremely more important than time based maintenance
- 7 Corrective maintenance is very strongly more important than time based maintenance
- 5 Corrective maintenance is strongly more important than time based maintenance
- 3 Corrective maintenance is moderately more important than time based maintenance
- 1 Corrective maintenance and time based maintenance are equally important
- 3 Time based maintenance is moderately more important than corrective maintenance

- 5 Time based maintenance is strongly more important than corrective maintenance
- 7 Time based maintenance is very strongly more important than corrective maintenance
- 9 Time based maintenance is extremely more important than corrective maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and CONDITION BASED MAINTENANCE (CBM) with respect to Availability on demand/Availability

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you the equipment is run until it fails. Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Corrective maintenance is extremely more important than condition based maintenance
- 7 Corrective maintenance is very strongly more important than condition based maintenance
- 5 Corrective maintenance is strongly more important than condition based maintenance
- 3 Corrective maintenance is moderately more important than condition based maintenance
- 1 Corrective maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than corrective maintenance
- 5 Condition based maintenance is strongly more important than corrective maintenance
- 7 Condition based maintenance is very strongly more important than corrective maintenance
- 9 Condition based maintenance is extremely more important than corrective maintenance

Compare the relative importance between TIME BASED MAINTENANCE (TBM) and CONDITION BASED MAINTENANCE (CBM) with respect to Availability on demand/Availability

"Please provide your judgement with respect to this particular sub-criterion". Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine". Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Time based maintenance is extremely more important than condition based maintenance

- ◌ 7 Time based maintenance is very strongly more important than condition based maintenance
- ◌ 5 Time based maintenance is strongly more important than condition based maintenance
- ◌ 3 Time based maintenance is moderately more important than condition based maintenance
- ◌ 1 Time based maintenance and condition based maintenance are equally important
- ◌ 3 Condition based maintenance is moderately more important than time based maintenance
- ◌ 5 Condition based maintenance is strongly more important than time based maintenance
- ◌ 7 Condition based maintenance is very strongly more important than time based maintenance
- ◌ 9 Condition based maintenance is extremely more important than time based maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and TIME BASED MAINTENANCE (TBM) with respect to Mean Time To Repair (MTTR)/Availability

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you run the equipment until it fails. Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine".

- ◌ 9 Corrective maintenance is extremely more important than time based maintenance
- ◌ 7 Corrective maintenance is very strongly more important than time based maintenance
- ◌ 5 Corrective maintenance is strongly more important than time based maintenance
- ◌ 3 Corrective maintenance is moderately more important than time based maintenance
- ◌ 1 Corrective maintenance and time based maintenance are equally important
- ◌ 3 Time based maintenance is moderately more important than corrective maintenance
- ◌ 5 Time based maintenance is strongly more important than corrective maintenance
- ◌ 7 Time based maintenance is very strongly more important than corrective maintenance
- ◌ 9 Time based maintenance is extremely more important than corrective maintenance

Compare the relative importance between CORRECTIVE MAINTENANCE (CM) and CONDITION BASED MAINTENANCE (CBM) with respect to Mean Time To Repair (MTTR)/Availability

"Please provide your judgement with respect to this particular sub-criterion". corrective maintenance CM is the form of maintenance when you the equipment is run until it fails. Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Corrective maintenance is extremely more important than condition based maintenance
- 7 Corrective maintenance is very strongly more important than condition based maintenance
- 5 Corrective maintenance is strongly more important than condition based maintenance
- 3 Corrective maintenance is moderately more important than condition based maintenance
- 1 Corrective maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than corrective maintenance
- 5 Condition based maintenance is strongly more important than corrective maintenance
- 7 Condition based maintenance is very strongly more important than corrective maintenance
- 9 Condition based maintenance is extremely more important than corrective maintenance

Compare the relative importance between TIME BASED MAINTENANCE (TBM) and CONDITION BASED MAINTENANCE (CBM) with respect to Mean Time To Repair (MTTR)/Availability

"Please provide your judgement with respect to this particular sub-criterion". Time based maintenance is a periodic maintenance " it can be planned hourly, daily, weekly and monthly or based of the number of operations of the machine". Condition based maintenance is the form of maintenance when the equipment is run until it shows a sign of degradation "equipment health can be observed by visual mentor, pressure or temperature change and any other form of monitoring".

- 9 Time based maintenance is extremely more important than condition based maintenance
- 7 Time based maintenance is very strongly more important than condition based maintenance
- 5 Time based maintenance is strongly more important than condition based maintenance
- 3 Time based maintenance is moderately more important than condition based maintenance

- 1 Time based maintenance and condition based maintenance are equally important
- 3 Condition based maintenance is moderately more important than time based maintenance
- 5 Condition based maintenance is strongly more important than time based maintenance
- 7 Condition based maintenance is very strongly more important than time based maintenance
- 9 Condition based maintenance is extremely more important than time based maintenance

If you have any comment or suggestions you would like to advise in regards to the hierarchy structure in terms of more criteria or alternative or any other information please add it in the following box.

Appendix (C): Total Maintenance Cost for Major Service

time/h	failure probability	Corrective cost	Preventive cost	Total Maintenance cost
168	0.0000000001	1.13455E-05	3280.842	3280.842
336	0.0000000022	0.000479055	3280.841993	1640.420996
504	0.0000000199	0.004278371	3280.841935	1093.613978
672	0.0000000943	0.020227752	3280.841691	820.2104227
840	0.0000003146	0.067493451	3280.840968	656.1681936
1008	0.0000008420	0.180650951	3280.839237	546.8065396
1176	0.0000019357	0.415291152	3280.835649	468.6908071
1344	0.0000039811	0.854100051	3280.828939	410.1036178
1512	0.0000075201	1.613361171	3280.817328	364.53526
1680	0.0000132835	2.849842101	3280.798419	328.0798457
1848	0.0000222244	4.76803414	3280.769085	298.2517447
2016	0.0000355537	7.627719091	3280.725354	273.3938021
2184	0.0000547768	11.75184055	3280.662286	252.3586869
2352	0.0000817312	17.5346591	3280.573853	234.3268062
2520	0.0001186263	25.45017194	3280.452806	218.697055
2688	0.0001680837	36.0607776	3280.290544	205.0185379
2856	0.0002331780	50.02616591	3280.07698	192.946391
3024	0.0003174802	68.1124122	3279.800398	182.2123349
3192	0.0004251001	91.20125236	3279.447314	172.6045316
3360	0.0005607306	120.2995131	3279.002331	163.9534912
3528	0.0007296923	156.5486675	3278.447995	156.1220148
3696	0.0009379783	201.2344819	3277.764641	148.9978896
3864	0.0011922995	255.7967156	3276.930254	142.4885045
4032	0.0015001297	321.8388257	3275.920311	136.5168265
4200	0.0018697511	401.1376274	3274.707642	131.018363
4368	0.0023102979	495.6528448	3273.262277	125.9388475
4536	0.0028318011	607.5364854	3271.551308	121.2324673
4704	0.0034452302	739.1419535	3269.538744	116.8605022
4872	0.0041625341	893.0328134	3267.185383	112.7902828
5040	0.0049966803	1071.991093	3264.448681	108.9943992
5208	0.0059616905	1279.025012	3261.282635	105.4501135
5376	0.0070726733	1517.375993	3257.637676	102.1389383
5544	0.0083458530	1790.524818	3253.460575	99.0463575
5712	0.0097985936	2102.196742	3248.694363	96.16166966
5880	0.0114494166	2456.365392	3243.278273	93.4779416
6048	0.0133180128	2857.255251	3237.147704	90.9920638
6216	0.0154252461	3309.342474	3230.234205	88.70490222
6384	0.0177931485	3817.35383	3222.465491	86.62154442
6552	0.0204449053	4386.263479	3213.765496	84.7516394
6720	0.0234048283	5021.28731	3204.054456	83.10983336
6888	0.0266983170	5727.874548	3193.24904	81.71630427

Time/h	failure probability	Corrective cost	Preventive cost	Total Maintenance cost
7056	0.0303518052	6511.69631	3181.262523	80.59740041
7224	0.0343926917	7378.630779	3168.005013	79.78638882
7392	0.0388492544	8334.744671	3153.383735	79.32432127
7560	0.0437505443	9386.270644	3137.303377	79.26102628
7728	0.0491262603	10539.58032	3119.666502	79.6562374
7896	0.0550066014	11801.15257	3100.374032	80.58086886
8064	0.0614220949	13177.53678	3079.325811	82.11845158
8232	0.0684034009	14675.31077	3056.421249	84.36674377
8400	0.0759810896	16301.03311	3031.56005	87.43953236
8568	0.0841853925	18061.18966	3004.643029	91.46864358
8736	0.0930459253	19962.13422	2975.57302	96.60618333
8904	0.1025913831	22010.02304	2944.255881	103.027031
9072	0.1128492078	24210.74352	2910.601579	110.9316137
9240	0.1238452279	26569.83693	2874.525375	120.5489927
9408	0.1356032727	29092.41562	2835.949088	132.1402975
9576	0.1481447621	31783.07504	2794.802442	146.0025517
9744	0.1614882756	34645.80122	2751.024483	162.4729401
9912	0.1756491025	37683.87438	2704.565047	181.9335769
10080	0.1906387799	1.13455E-05	2655.386284	204.8168486
10248	0.2064646221	0.80936122	2603.464196	231.611416
10416	0.2231292489	0.793535378	2548.790189	262.8689811
10584	0.2406301200	0.776870751	2491.372596	299.2119455
10752	0.2589590847	0.75936988	2431.238159	341.3421155
10920	0.2781019552	0.741040915	2368.433425	390.0506423
11088	0.2980381163	0.721898045	2303.02603	446.2294296
11256	0.3187401805	0.701961884	2235.105829	510.8842933
11424	0.3401737020	0.68125982	2164.785831	585.150223
11592	0.3622969625	0.659826298	2092.202909	670.3091787
11760	0.3850608400	0.637703037	2017.518224	767.8109543
11928	0.4084087740	0.61493916	1940.917341	879.2977697
12096	0.4322768395	0.591591226	1862.609989	1006.633409
12264	0.4565939396	0.56772316	1782.829426	1151.937923
12432	0.4812821265	0.54340606	1701.831386	1317.629153
12600	0.5062570588	0.518717874	1619.892579	1506.472669
12768	0.5314285990	0.493742941	1537.308732	1721.642078
12936	0.5567015538	0.468571401	1454.392161	1966.792191
13104	0.5819765546	0.443298446	1371.468877	2246.148149
13272	0.6071510726	0.418023445	1288.875261	2564.614456
13440	0.6321205588	0.392848927	1206.954322	3280.842

Appendix (D): The Weekly Movement of Part (1)

Weeks	on hand	Weeks	on hand	Weeks	on hand	Weeks	on hand
1	52	45	30	89	38	133	46
2	52	46	30	90	38	134	46
3	52	47	30	91	38	135	46
4	52	48	30	92	38	136	46
5	52	49	30	93	38	137	46
6	52	50	30	94	38	138	46
7	52	51	30	95	38	139	46
8	52	52	30	96	38	140	46
9	52	53	30	97	38	141	46
10	52	54	30	98	38	142	46
11	54	55	32	99	40	143	48
12	54	56	32	100	40	144	48
13	54	57	32	101	40	145	48
14	54	58	32	102	40	146	48
15	54	59	32	103	40	147	48
16	54	60	32	104	40	148	48
17	54	61	32	105	40	149	48
18	54	62	32	106	40	150	48
19	54	63	32	107	40	151	48
20	54	64	32	108	40	152	48
21	54	65	32	109	40	153	48
22	26	66	34	110	42	154	50
23	26	67	34	111	42	155	50
24	26	68	34	112	42	156	50
25	26	69	34	113	42	157	50
26	26	70	34	114	42	158	50
27	26	71	34	115	42	159	50
28	26	72	34	116	42	160	50
29	26	73	34	117	42	161	50
30	26	74	34	118	42	162	50
31	26	75	34	119	42	163	50
32	26	76	34	120	42	164	50
33	28	77	36	121	44	165	52
34	28	78	36	122	44	166	52
35	28	79	36	123	44	167	52
36	28	80	36	124	44	168	52
37	28	81	36	125	44	169	52
38	28	82	36	126	44	170	52
39	28	83	36	127	44	171	52
40	28	84	36	128	44	172	52
41	28	85	36	129	44	173	52
42	28	86	36	130	44	174	52
43	28	87	36	131	44	175	52
44	30	88	38	132	46	176	54

Weeks	on hand	Weeks	on hand	Weeks	on hand	Weeks	on hand
177	54	221	32	265	40	309	48
178	54	222	32	266	40	310	48
179	54	223	32	267	40	311	48
180	54	224	32	268	40	312	48
181	54	225	32	269	40	313	48
182	54	226	32	270	40	314	48
183	54	227	32	271	40	315	48
184	54	228	32	272	40	316	48
185	54	229	32	273	40	317	48
186	54	230	32	274	40	318	48
187	26	231	34	275	42	319	50
188	26	232	34	276	42	320	50
189	26	233	34	277	42	321	50
190	26	234	34	278	42	322	50
191	26	235	34	279	42	323	50
192	26	236	34	280	42	324	50
193	26	237	34	281	42	325	50
194	26	238	34	282	42	326	50
195	26	239	34	283	42	327	50
196	26	240	34	284	42	328	50
197	26	241	34	285	42	329	50
198	28	242	36	286	44	330	52
199	28	243	36	287	44	331	52
200	28	244	36	288	44	332	52
201	28	245	36	289	44	333	52
202	28	246	36	290	44	334	52
203	28	247	36	291	44	335	52
204	28	248	36	292	44	336	52
205	28	249	36	293	44	337	52
206	28	250	36	294	44	338	52
207	28	251	36	295	44	339	52
208	28	252	36	296	44	340	52
209	30	253	38	297	46	341	54
210	30	254	38	298	46	342	54
211	30	255	38	299	46	343	54
212	30	256	38	300	46	344	54
213	30	257	38	301	46	345	54
214	30	258	38	302	46	346	54
215	30	259	38	303	46	347	54
216	30	260	38	304	46	348	54
217	30	261	38	305	46	349	54
218	30	262	38	306	46	350	54
219	30	263	38	307	46	351	54
220	32	264	40	308	48	352	26

Weeks	on hand	Weeks	on hand	Weeks	on hand	Weeks	on hand
353	26	397	34	441	42	485	50
354	26	398	34	442	42	486	50
355	26	399	34	443	42	487	50
356	26	400	34	444	42	488	50
357	26	401	34	445	42	489	50
358	26	402	34	446	42	490	50
359	26	403	34	447	42	491	50
360	26	404	34	448	42	492	50
361	26	405	34	449	42	493	50
362	26	406	34	450	42	494	50
363	28	407	36	451	44	495	52
364	28	408	36	452	44	496	52
365	28	409	36	453	44	497	52
366	28	410	36	454	44	498	52
367	28	411	36	455	44	499	52
368	28	412	36	456	44	500	52
369	28	413	36	457	44	501	52
370	28	414	36	458	44	502	52
371	28	415	36	459	44	503	52
372	28	416	36	460	44	504	52
373	28	417	36	461	44	505	52
374	30	418	38	462	46	506	54
375	30	419	38	463	46	507	54
376	30	420	38	464	46	508	54
377	30	421	38	465	46	509	54
378	30	422	38	466	46	510	54
379	30	423	38	467	46	511	54
380	30	424	38	468	46	512	54
381	30	425	38	469	46	513	54
382	30	426	38	470	46	514	54
383	30	427	38	471	46	515	54
384	30	428	38	472	46	516	54
385	32	429	40	473	48	517	26
386	32	430	40	474	48	518	26
387	32	431	40	475	48	519	26
388	32	432	40	476	48	520	26
389	32	433	40	477	48	521	26
390	32	434	40	478	48	522	26
391	32	435	40	479	48	523	26
392	32	436	40	480	48	524	26
393	32	437	40	481	48	525	26
394	32	438	40	482	48	526	26
395	32	439	40	483	48	527	26
396	34	440	42	484	50	528	28

Weeks	on hand	Weeks	on hand	Weeks	on hand	Weeks	on hand
529	28	573	36	573	36	617	44
530	28	574	36	574	36	618	44
531	28	575	36	575	36	619	44
532	28	576	36	576	36	620	44
533	28	577	36	577	36	621	44
534	28	578	36	578	36	622	44
535	28	579	36	579	36	623	44
536	28	580	36	580	36	624	44
537	28	581	36	581	36	625	44
538	28	582	36	582	36	626	44
539	30	583	38	583	38	627	46
540	30	584	38	584	38	628	46
541	30	585	38	585	38	629	46
542	30	586	38	586	38	630	46
543	30	587	38	587	38	631	46
544	30	588	38	588	38	632	46
545	30	589	38	589	38	633	46
546	30	590	38	590	38	634	46
547	30	591	38	591	38	635	46
548	30	592	38	592	38	636	46
549	30	593	38	593	38	637	46
550	32	594	40	594	40	638	48
551	32	595	40	595	40	639	48
552	32	596	40	596	40	640	48
553	32	597	40	597	40	641	48
554	32	598	40	598	40	642	48
555	32	599	40	599	40	643	48
556	32	600	40	600	40	644	48
557	32	601	40	601	40	645	48
558	32	602	40	602	40	646	48
559	32	603	40	603	40	647	48
560	32	604	40	604	40	648	48
561	34	605	42	605	42	649	50
562	34	606	42	606	42	650	50
563	34	607	42	607	42	651	50
564	34	608	42	608	42	652	50
565	34	609	42	609	42	653	50
566	34	610	42	610	42	654	50
567	34	611	42	611	42	655	50
568	34	612	42	612	42	656	50
569	34	613	42	613	42	657	50
570	34	614	42	614	42	658	50
571	34	615	42	615	42	659	50
572	36	616	44	616	44	660	52

Weeks	on hand	Weeks	on hand	Weeks	on hand	Weeks	on hand
661	52	705	30	749	38	793	46
662	52	706	30	750	38	794	46
663	52	707	30	751	38	795	46
664	52	708	30	752	38	796	46
665	52	709	30	753	38	797	46
666	52	710	30	754	38	798	46
667	52	711	30	755	38	799	46
668	52	712	30	756	38	800	46
669	52	713	30	757	38	801	46
670	52	714	30	758	38	802	46
671	54	715	32	759	40	803	48
672	54	716	32	760	40	804	48
673	54	717	32	761	40	805	48
674	54	718	32	762	40	806	48
675	54	719	32	763	40	807	48
676	54	720	32	764	40	808	48
677	54	721	32	765	40	809	48
678	54	722	32	766	40	810	48
679	54	723	32	767	40	811	48
680	54	724	32	768	40	812	48
681	54	725	32	769	40	813	48
682	26	726	34	770	42	814	50
683	26	727	34	771	42	815	50
684	26	728	34	772	42	816	50
685	26	729	34	773	42	817	50
686	26	730	34	774	42	818	50
687	26	731	34	775	42	819	50
688	26	732	34	776	42	820	50
689	26	733	34	777	42	821	50
690	26	734	34	778	42	822	50
691	26	735	34	779	42	823	50
692	26	736	34	780	42	824	50
693	28	737	36	781	44	825	52
694	28	738	36	782	44	826	52
695	28	739	36	783	44	827	52
696	28	740	36	784	44	828	52
697	28	741	36	785	44	829	52
698	28	742	36	786	44	830	52
699	28	743	36	787	44	831	52
700	28	744	36	788	44	832	52
701	28	745	36	789	44	833	52
702	28	746	36	790	44	834	52
703	28	747	36	791	44	835	52
704	30	748	38	792	46	836	54

Weeks	on hand	Weeks	on hand	Weeks	on hand	Weeks	on hand
837	54	848	26	859	28	870	30
838	54	849	26	860	28	871	30
839	54	850	26	861	28	872	30
840	54	851	26	862	28	873	30
841	54	852	26	863	28	874	30
842	54	853	26	864	28	875	30
843	54	854	26	865	28	876	30
844	54	855	26	866	28	877	30
845	54	856	26	867	28	878	30
846	54	857	26	868	28	879	30
847	26	858	28	869	30	880	32