DEVELOPMENT OF A RISK-BASED MAINTENANCE STRATEGY FOR THE MULTIPRODUCT PETROLEUM PIPELINE SYSTEM IN KENYA

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Development of a risk-based maintenance strategy for the multiproduct petroleum pipeline system in Kenya

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university.

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This thesis has been submitted for examination with our approval as the university supervisors.

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DEDICATION

This thesis is dedicated to my mum, *Esekon Achilla*, my wife, *Lilian Aleper* and my children, *Daphine Esekon* and *Luis Lochuch*.

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ABBREVIATIONS

AGO	Automotive Gas Oil
AHP	Analytic Hierachy Process
BCM	Business Centred Maintenance
CBM	Condition Based Maintenance
CI	Consistency Index
CIBOCOF	Centre Industrieel Beleid Onderhouds Ontwikkelings Framework (Centre for Industrial Management Maintenance Concept Development Framework)
CM	Corrective Maintenance
Cm	Consistency measure
CR	Consistency Ratio
DOM	Design Out Maintenance
DOT-OPS	Department of Transport-Office of Pipeline Safety
DPK	Dual Purpose Kerosene
DTs	Decision Trees
EGIG	European Gas Pipeline Incident Data Group
ETA	Event Tree Analysis
FBM	Failure Based Maintenance
FMEA	Failure Mode and Effects Analysis
FTA	Fault Tree Analysis
HAZOP	Hazard and Operability analysis
HPP	Homogeneous Poisson Process
HSE	Health and Safety Executive
IK	Illuminating Kerosine
KOSF	Kipevu Oil Storage Facility

KPC	Kenya Pipeline Company
LCC	Life Cycle Costing
LNG	Liquified Natural Gas
MFL	Magnetic Flux Leakage
MIC	Microbial Induced Corrosion
MIL-HDBK	Military Handbook
MSP	Motor Spirit Premium
MSR	Motor Spirit Regular
NHPP	Non-Homogeneous Poisson Process
NLH	Non Linear Harmonic
OBM	Opportunity Based Maintenance
PHMSA	Pipeline and Hazardous Materials Safety Administration
PHA	Preliminary Hazard Analysis
PS	Pump Station
QRA	Quantitative/Qualitative Risk Assessment
RBM	Risk Based Maintenance
RCM	Reliability Centred Maintenance
RI	Random Index
RPN	Risk Priority Number
TPM	Total Productive Maintenance
T/UBM	Time/Use Based Maintenance

ABSTRACT

The Kenya multiproduct petroleum pipeline is a vital asset in the sustainance of the national economy. Without proper maintenance, the pipeline system may be susceptible to different degrees of failure, degradation and safety related incidences. Pipeline system failures are often fatal and very disastrous. The Kenya pipeline currently utilizes the routine preventive and break-and-fix maintenance practices. The pipeline system experiences occasional equipment failures and safety related incidences that lead to shortages in the supply of petroleum products in the retail market and loss of human lives. In this study, a risk-based maintenance strategy for application in the maintenance of the pipeline system is developed. Failure Mode and Effects Analysis, risk matrix, Root Cause Analysis, and Analytic Hierarchy Process were applied in developing the strategy. The risk factors identified were equipment failure, sabotage/-vandalism, human/operator error, mechanical damage, external and internal corrosion, construction/weld defect, and natural hazard. Results show that equipment failure is the most prevalent risk factor at 40% followed by sabotage/vandalism at 25% and human/operator error, mechanical damage, external corrosion, internal corrosion, construction/weld defect and natural hazard at 18%, 5%, 5%, 4%, 2% and 1%, respectively. From the analytic hierarchy process analysis, condition based maintenance was identified as the most prefered maintenance policy for the pipeline system, followed by time based maintenance, failure based maintenance and design out maintenance in that order. It is recommended that maintenance managers and other personnel responsible for pipeline system equipment maintenance should adopt an inspection and maintenance policy for the company based on the decision framework and risk based maintenance approach developed in this study. The risk based maintenance approach applied to the multiproduct pipeline system can lead to increased safety, reduced maintenance costs, maximized throughput, and reduced catastrophic failures.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Research Background

Kenya's petroleum products are transported mainly through a multiproduct pipeline. This pipeline is very vital for the sustainance of the national economy. The pipeline plays a critical role in fostering development and growth by ensuring sufficient and reliable supply of petroleum products. Apart from the domestic market, the pipeline system serves the neighbouring countries of Uganda, Rwanda, Eastern Democratic Republic of Congo, Northern Tanzania, Burundi and Southern Sudan.

Like any other engineering facility, petroleum pipeline facilities are subject to failure and degradation if not properly maintained. Failures associated with these facilities are often very disastrous. It is therefore important that they are effectively monitored for optimal operation, while reducing failures to acceptable safety limits through proper maintenance.

The Kenya pipeline system occasionally experiences unexpected failures which lead to downtime and loss of product through spillages among other effects. Among consequences arising from these failures and safety related incidences are product shortages in the retail outlets, revenue and equipment losses, environmental degradation and loss of human lives. The Sinai slum incident experienced on 12^{th} September, 2011 is the most recent Kenya pipeline disaster where 100 lives were lost with over 120 people hospitalized with severe burns [1].

Petroleum pipeline failures are usually as a result of external interference, corrosion, operational errors and structural defects. External interference is by either sabotage or mechanical damage. Corrosion could be either internal or external whereas operational errors are human related, occurring due to negligence or lack of knowledge of an operator. Structural defects occur mostly due to deformation in the pipeline material or as a result of construction defects that occur during the fabrication process.

Among the incidents/accidents that have occurred in the pipeline system are: Flange gasket rupture at Line I (km 40) which resulted in product spill of 192 m^3 on 31^{st} October, 2013 [2]; line I (Km 185.9) rupture which led to a spillage of 105 m^3 on 30^{th} September, 2013 [2]; worn-out pig hatch O-ring at PS5 which led to a spillage of 2 m^3 on 30^{th} September, 2012 [3].

To be able to identify the failure factors and to select appropriate maintenance strategies for the Kenya pipeline system, this thesis develops a risk based maintenance strategy that utilizes Failure Mode and Effects Analysis (FMEA) [4], Risk Priority Number (RPN) [5] and risk matrix for identification of failure factors and risk analysis [6]. The root cause analysis (RCA) methodology [7] is also applied in risk evaluation whereas analytic hierarchy process (AHP) [8] is used to select appropriate maintenance policies.

1.2 Brief on the petroleum pipeline industry in Kenya

Kenya has one pipeline network managed by the Kenya Pipeline Company (KPC), which is a state corporation established in 1973 under the Companies Act (CAP 486) of the Laws of Kenya. The company started commercial operations in 1978. The main objective of the Company is to provide efficient, reliable, safe and cost effective means of transporting petroleum products from Mombasa to the hinterland. In pursuit of this objective, the Company constructed a pipeline network, storage and loading facilities for transportation, storage and distribution of petroleum products [9].

The construction of Mombasa - Nairobi pipeline (line I) began in October 1976, and was completed and commissioned in 1978. Later the Western Kenya Pipeline Extension (WKPE) which runs from Nairobi to Eldoret (line II) and from Sinendet to Kisumu (line III), was constructed and commissioned in 1994. The petroleum pipeline system transports Motor Spirit Premium (MSP) - petrol, Automotive Gas Oil (AGO) - diesel, Jet A-1 and Illuminating Kerosene (IK).

The Mombasa - Nairobi pipeline (line I) system consists of a 450 kilometre, 14-inch diameter pipeline. Prior to 2008, the system's installed flow rate was 440 m^3/hour (translating to delivery of 3.85 billion litres per year). The products flow was controlled at four Pump Stations located at Changamwe, Mombasa (PS1) through which products are received into the pipeline system, Maungu (PS3), Mtito Andei (PS5) and at Sultan Hamud (PS7). The design of the Mombasa - Nairobi pipeline system had provision for installation of additional future Pump Stations at Samburu (PS2), Manyani (PS4), Makindu (PS6), Konza (PS8) to increase the flow rate to up to 880 m^3/hr [9].

As a result of regional economic growth and the rise in petroleum products demand, the pipeline traffic experienced a marked increase, rising from 879,776 m^3 in 1978 to 3,853,439 m^3 in the year 2007. The Mombasa - Nairobi Pipeline system experienced capacity constraints, subsequently, KPC embarked on a Capacity Enhancement Project which entailed construction of the four additional Pump Stations. Commissioning of the four new pump stations on the Mombasa - Nairobi Pipeline system in November, 2008 was a major milestone in the enhancement of the petroleum products supply in the region.

The WKPE consists of 446 kilometre, 8-inch (line II) and 6 inch (line III) diameter pipelines. At commissioning in 1994, WKPE had a combined flow rate of 160 m^3/hr. This flow rate was attained with only three Pump Stations located at Nairobi (PS 21), Ngema (PS 22) and Nakuru (PS 24). Following the increase in demand for products in Western Kenya and the neighbouring countries, the system's flow rate was enhanced in 2004 to 220 m^3/hr through construction of a Pump Station at Morendat (PS23).

KPC in its bid to enhance the capacity of the WKPE in 2010, began the construction of a parallel 14-inch diameter multi-product pipeline from Nairobi to Eldoret. The pipeline extension was commissioned in November 2011 and increased the combined flow rate to Western Kenya by an additional 378 m^3/hr. Ultimately, the 14-inch diameter parallel pipeline will be able to achieve a flow rate of 757 m^3/hr through phased installation of additional pumps.

Total length of the Pipeline network is 1221 Km. The pipeline sections lengths and diameters are: Mombasa-Nairobi (Line I) - 450 kms with a 14 inch diameter pipe; Nairobi - Eldoret (Line II) - 325 kms with a 8 inch diameter pipe from Nairobi to Burnt Forest and a 6 inch diameter pipe from Burnt Forest to Eldoret; Sinendet-Kisumu (Line III) - 121 kms with a 6 inch diameter pipe. Line IV (Nairobi-Eldoret) is 325 Kms long and has a 14 inch diameter pipe. This network is shown in figure 1.1 [10].

The total pipeline system tank storage capacity is 971,604 m^3. The capacity per depot is: Kipevu Oil Storage Facility (KOSF) - 527,493 m^3; Moi Airport (Mombasa) - 5,513 m^3; JKIA (Embakasi) - 54,141 m^3; Nairobi - 167,863 m^3; Nakuru - 58,438 m^3; Eldoret - 82,110 m^3; and Kisumu - 76,046 m^3.

Figure 1.1: Kenya petroleum pipeline network

1.3 Problem statement

Petroleum pipeline system requires high standards of safety and maintenance owing to the high risks involved in handling it. The pipeline system experiences unexpected failures from corrosion, external interference, and operational error related incidences which have led to downtime and loss of product through spillages, among other effects.

These failures and safety related incidences have led to product pumping stoppages resulting to product shortages in the retail market; oil spillages resulting to revenue and equipment losses as well as environmental degradation and even loss of human lives.

The Kenya petroleum pipeline system utilizes the routine preventive and the break-and-fix maintenance approaches. The maintenance approach through schedules of 3,000 hours, 6,000 hours and 10,000 hours. Corrective maintenance is applied when the pipeline equipment fail. Safety issues arising from the pipeline system have a relationship with the maintenance practices employed. There is need therefore to break away from these maintenance practices and to incorporate a practice that prioritizes pipeline system maintenance based on the analysis of the risks involved and the consequences associated with those risks. Identification of risk factors can also have an effect of increased system efficiency and safety of the pipeline system.

This research has developed a risk-based maintenance strategy in the maintenance of the petroleum pipeline system. Risk-based maintenance (RBM) approach applied to the multiproduct pipeline system is expected to lead to increased safety, reduced maintenance costs, maximized productivity and reduced catastrophic failures.

1.4 Justification of the study

The research will help the pipeline operator in risk assessment of pipeline equipment and facilities, which will help in effective allocation of inspection and maintenance efforts. The RBM approach applied to multiproduct pipeline system will lead to increased safety, reduced maintenance costs and maximized productivity.

1.5 Study objectives

1.5.1 Main objective

The main objective of this study is to develop a risk-based maintenance strategy for application in the management of the Kenya multiproduct petroleum pipeline system.

1.5.2 Specific objectives

The following are the specific objectives:

(a) To identify the risk factors in the petroleum pipeline system.

(b) To evaluate pipeline system risks.

(c) To formulate a framework for maintenance policy selection.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Definition of Maintenance

Maintenance is "the combination of all technical and administrative actions, including supervision actions, intended to monitor, control and retain an item, machine or process in, or restore it to, a state in which it can perform a required function" [11]. The need for maintenance is predicated on actual or impending failure. Ideally, maintenance is performed to keep equipment and systems running efficiently for at least design life of the component(s).

2.2 Maintenance approaches

Maintenance approaches can broadly be categorized as either corrective maintenance (CM) or preventive maintenance (PM). In corrective maintenance, maintenance activity is undertaken after the equipment has failed. CM is sometimes regarded as all actions performed after a failure in order to restore an item to a specified condition [12]. In contrast, preventive maintenance is carried out while the equipment is still in operation. According to Moghaddam and Usher [13], preventive maintenance includes all actions performed in order to improve the overall reliability and availability of a system, by providing systematic inspection, detection, and prevention of developing failures.

Preventive and corrective maintenance planning Models, techniques and policies have been extensively studied, experimented and documented in the past. Edward and Claude [14] presented a study on preventive maintenance with limited historical data. Lai K.K. et al. [15] studied on practices of preventive maintenance and replacement for engines. In a research by Hongzhou Wang [12] a survey of maintenance policies of deteriorating systems is presented. In a research by J. Jaturonnatee et al. [16] an optimal preventive maintenance through corrective minimal repair of leased equipment has been discussed. In a research by Ruey Huei Yeh et al. [17] a preventive maintenance policy for leased products considering all aspects of applicable maintenance costs is discussed.

Various maintenance approaches are provided in the literature. Figure 2.1 shows the classification of maintenance. From this figure, preventive maintenance is either on-condition or pre-determined. On-condition means that maintenance is done based on the condition of the equipment at a particular time and maintenance can be scheduled, on-request or continuous. Pre-determined preventive maintenance is done at certain time intervals and is scheduled. Corrective maintenance can either be done immediately or is deferred based on the state of the equipment at the time of failure [13].

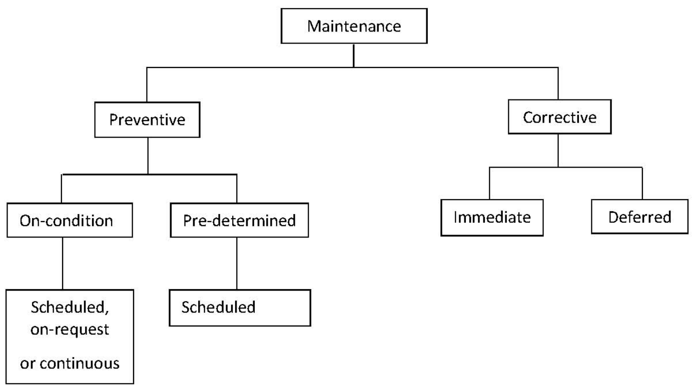

Figure 2.1: Maintenance approaches

Table 2.1 shows a comparison of corrective and preventive maintenance approaches in terms of their advantages and disadvantages [13].

Table 2.1: Comparison of maintenance approaches

Approach	Advantages	Disadvantages
Corrective maintenance	-No over maintenance (low cost policy). -No condition related cost. -Requires minimal management. -Useful on small non-integrated plant.	-High production downtime. -Large spare inventory. -High cost repairs. -Crisis management needed. -Overtime labour
Preventive maintenance	-Enabled management control. -Reduced downtime. -Control over spare parts and costs. -Reduced unexpected failure. -Fewer catastrophic failures.	-Over- maintenance. -Unscheduled breakdowns.

2.3 Maintenance concepts and actions

A maintenance concept is a set of maintenance policies and actions of various types and the general decision structure in which these are planned and supported. Maintenance concepts include total productive maintenance,reliability centred maintenance and total quality maintenance among others [18]. A maintenance action is the basic maintenance intervention and elementary task carried out by a technician after an equipment failure, whereas a maintenance policy is a rule or set of rules describing the triggering mechanism for the different maintenance actions. Maintenance policies include include time/use based maintenance, condition based maintenance, design out maintenance and failure based maintenance [18].

Figure 2.2 shows the relationship between Maintenance Action, Policy, and Concepts [19]:

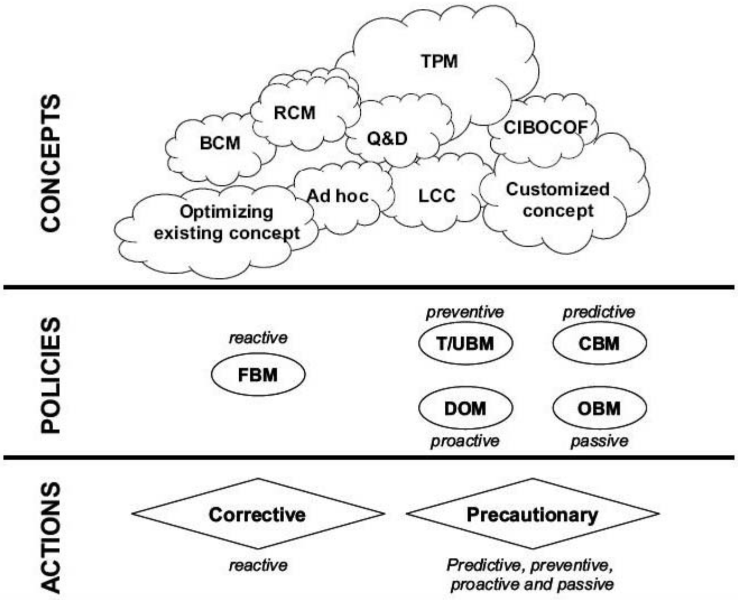

Figure 2.2: Relationships between Maintenance Actions, Policies, and Concepts

In figure 2.2, maintenance actions are either corrective or precautionary. Corrective/reactive action is that intervention after an equipment has failed. Precautionary includes preventive, predictive, proactive and passive actions. Preventive action recognizes that some failures on a component have a direct relation with time and its cycle of use and is based on physical wear of components or age-related fatigue characteristics. Predictive maintenance actions involve inspection and condition based monitoring. Proactive maintenance actions involve setting design requirements for installations at earlier product stages in order to avoid later consequences. Passive maintenance actions are driven by the opportunity of other maintenance actions being planned.

Maintenance action has a direct impact on maintenance policies. Several types of maintenance policies can be considered to trigger, in one way or another, either precautionary or corrective maintenance interventions. A maintenance concept is necessary to plan, control and improve the various maintenance actions and policies applicable to an installation.

Some maintenance concepts are illustrated in the following sub-sections.

2.3.1 Reliability centered maintenance (RCM)

Reliability centered maintenance (RCM) is defined as "a process used to determine the maintenance requirements of any physical asset in its operating context" [20]. Basically, RCM recognizes that all equipment in a facility are not of equal importance to either the process or facility safety. It recognizes that equipment design and operation differs and that different equipment will have a higher probability to undergo failures from different degradation mechanisms than others [21].

2.3.2 Total productive maintenance (TPM)

The focus of TPM is to develop quality maintenance workers and adopt a zero defect, zero loss, and zero failure approach towards maintenance management. TPM is often viewed as a people-centred approach to maintenance. A main feature of TPM is to eliminate all machine losses to maximise overall equipment effectiveness. Another main feature is the use of small work groups to investigate and solve recurring problems and failures in the plant [22].

2.3.3 Total Quality Maintenance (TQMain)

TQMain is a means for monitoring and controlling deviations in process condition and product quality. It is also a means for detecting failure causes and potential failures in order to interfere, arrest or reduce machine deterioration rate when possible before the product characteristics are intolerably affected and to perform the required action, to restore the machine/process or a particular part of it to as good as new [23]. The main objective of TQMain is to assure high quality products or services at competitive prices and also to enable the user to maintain and improve the technical and economic effectiveness of process elements continuously.

2.3.4 Risk based maintenance (RBM)

Risk based maintenance is defined as “a strategy that prioritizes maintenance resources toward assets that carry the most risk if they were to fail”. It is a methodology for determining the most economical use of maintenance resources. This is done so that the maintenance effort across a facility is optimized to minimize the total risk of failure [24].

In the past, maintenance of production systems used to be based purely on intuition, and sometimes using a break-and-fix approach. According to Thoft-Christensen [25] this approach is now considered crude and unacceptable under present safety criteria. Khan and Haddara [26] note that the field of maintenance management has evolved over the years from using primitive techniques to the application of more sophisticated maintenance strategies, such as routine based maintenance, condition monitoring, and reliability centered maintenance.

The cost of maintenance is a considerable part of petroleum pipeline systems. A study by Hale et al [27] evaluated safety in the management of maintenance activities in the chemical process industry in Netherlands. A theoretical model of an ideal maintenance management system incorporating safety was established and tested. Recommendations were made about strengthening maintenance engineering function responsible for coordinating the incorporation of safety into design, maintenance concept and planning and for the learning of lessons from incident and breakdown analysis, a function which can also contribute positively to an economic operation of the facility. A research by Dalzell [28] on “Is operating cost a direct measure of inherent safety?” offers a radical approach to considering the value of the reduction in likelihood and personnel exposure through the longevity and reliability of the plant. The study recommended that risk is proportional to the square of the operating cost. Hu et al [29] studied Risk-based maintenance strategy and its applications in a petrochemical reforming reaction system. The study proposes that Risk-based maintenance (RBM) strategy can be used in developing a cost-effective maintenance plan to make financial and safety improvements in a petrochemical system. It also proposed an improved RBM approach based on the proportional age reduction model. The results of this study showed that most equipment in this system are imperfectly repaired. The imperfect nature of the periodic preventive maintenance means it needs to be carried out more frequently.

In a further development, the high costs associated with maintenance of petroleum assets require the development of systematic and effective approaches for optimizing maintenance of the assets. This will also ensure adequate reliability and reduced life cycle cost of production assets according to Arunraj and Maiti [30]. The increased requirements of regulations on constructed facilities have further necessitated the need to take risk components into maintenance decisions.

For practical applications, a risk-based maintenance strategy can be formulated with the purpose of combining the requirements of asset maintenance with risk compliance and acceptability. RBM combines the assessment of risk to support inspection planning and maintenance decisions. The risk assessment requires either a qualitative or quantitative estimates of both the probability of failure and the consequences associated with equipment failure. Furthermore, risk based maintenance strategy utilises estimated risks to provide adequate recommendation on what, when and how equipment maintenance should be done.

In general, there are different ways of implementing Risk based maintenance. Chang et al. [31] proposed that risk can be expressed following a two-dimensional risk perspective, which is the product of the probability of failure and consequences. In this perspective, probability of failure depends on the likelihood that a given failure mechanism will occur, and the availability of relevant inspection and maintenance policies that are taken to mitigate the probability of failure. Consequences depend on the monetary components that describe the impact of a given hazard on people and the environment.

A number of researchers have modelled pipeline risks using quantitative risk assessment methods. Jo and Ahn [32] did a study on the method of quantitative risk assessment for transmission pipelines carrying natural gas. The study was useful for risk management during planning and building stages of a new pipeline and the modification of a burried pipeline. The research did not take an existing pipeline into consideration. Han and Weng [33] proposed an integrated quantitative risk analysis method for natural gas pipeline network. The QRA results were a determination of individual risk and societal risk caused by different accidents. Jo and Crowl [34] did a study on individual risk analysis of high pressure natural gas pipelines. The method is based on reasonable accident scenarios for route planning related to the pipeline's proximity to the surrounding buildings. The study recommends that pipeline operators and regulators must address the associated public safety issues.

Decision models have also found applications in risk analysis of oil and gas pipelines. Kallen and Noortwijk [35] proposed an adaptive Bayesian decision model to determine optimal inspection plans under uncertain deterioration. Their model uses Gamma stochastic process to model corrosion damage mechanism and Bayes' theorem to update prior knowledge over the corrosion rate with imperfect wall thickness measurements. Dey [36] presented a risk-based model for inspection and maintenance of a cross-country petroleum pipeline that reduces the amount of time spent on inspection. This model does not only reduce the cost of the pipeline maintenance; but also suggests efficient design and operational philosophies, construction methodology, and logical insurance plans. The risk-based model uses an analytical hierarchy process and a multiple attribute decision-making technique to identify the factors that influence the failure of a specific pipeline segment. This method could be used to prioritize the inspection and maintenance of pipeline segments.

2.4 Maintenance policies

Geert and Liliane [37] distinguished five basic policies in maintenance, time/use-based Maintenance (T/UBM), Condition-based Maintenance (CBM), Failure-based Maintenance (FBM), and Design-out Maintenance (DOM).

2.4.1 Time based maintenance

Time-based maintenance is defined as "maintenance performed on equipment based on a calendar schedule." This means that time is the maintenance trigger for this type of maintenance.

Time-based maintenance is planned maintenance and can be used with both preventative maintenance and predictive maintenance strategies. A maintenance plan for a piece of equipment is put together that needs to be performed regularly. With the maintenance plan in place, the maintenance is performed each time the calendar rolls over the specified number of days.

Ahmad and Kamaruddin [38] presents an overview of two maintenance techniques widely discussed in the literature: time-based maintenance (TBM) and condition-based maintenance (CBM). The paper discusses how the TBM and CBM techniques work toward maintenance decision making.

2.4.2 Condition Based Maintenance

BS-EN 13306 [39] defines Condition based maintenance(CBM) as: "Preventive maintenance based on performance and/or parameter monitoring and the subsequent actions." Jardine [40] also defines CBM as "a maintenance strategy that uses the actual condition of the asset to decide what maintenance needs to be done."
CBM is performed to serve the following two purposes [41]:

- To determine if a problem exists in the monitored item, how serious it is, and how long the item can be run before failure.
- To detect and identify specific components in the items which are degrading and diagnose the problem.

Unlike in planned scheduled maintenance, where maintenance is performed based upon predefined scheduled intervals, condition based maintenance is performed only when it is triggered by asset conditions. The goal of CBM is to spot impending failure to allow for proactive scheduling of maintenance.
Moubray [20], like Starr [42] however, points out that condition monitoring techniques are effective where appropriate, but a deep disappointment where not. Moubray [20] concludes that condition monitoring is only technically feasible for about 20% of all failure modes and worth doing in less than half of those cases. All on-condition tasks included increase this figure to about 25-35% of all failure modes. However, Starr [42] also points out that by implementing a condition based maintenance approach, there is much to gain in the form of:

- Reduced maintenance costs, less unnecessary repairs and replacements saving labor, spare parts, and unavailability.

- Damage limitation, incipient failures are easier to repair than breakdowns, also less secondary damage is at stake.
- Eliminated production losses.

2.4.3 Failure Based Maintenance

Failure-based Maintenance (FBM) is unscheduled maintenance or repair to return the equipment to a defined state. There are no interventions until a failure has occurred [43].

2.4.4 Design Out Maintenance

According to Gopalakrishnan and Banerji [44], DOM is a system that strives to eliminate, and if that is not possible, then to minimise the need for maintenance to the lowest possible level. It is therefore also known as "eliminative maintenance". Hence it has to be thought of and applied to the product at the design stage itself, so that machinery, plant, and equipment are so designed as to require the least possible amount of attention or maintenance during their economic life-span.

2.5 Maintenance of petroleum pipelines

The pipeline systems are the best way to transport petroleum products to customers. There are many reasons why pipelines are a popular means of transportation. First, distribution of petroleum products with pipelines are a safe and an economically efficient transportation method of carrying these products over long distances as compared to oil and gas tankers, trucks/railroad tank cars, and other transportation methods [45].

In 1998, the total number of fatalities due to pipeline incidents in the U.S. was twenty-seven ppm, which is much lower than the other transportation methods. According to the EIA (2013), "two-thirds of the lower 48 States in the U.S. are almost totally dependent upon the interstate pipeline system for their supplies of natural gas" [46]. Although pipelines are the safest and the most economical way of the carrying oil products, any release on pipelines can have an adverse effect on employees, customers, the public, or the environment [47]. Pipeline incidents can lead to many important consequences other than costs. Injuries and fatalities are the two obvious ones [48]. According to DOT/PHMSA pipeline incidents data, a total of 75 fatalities, 334 injuries, and Ksh.197,757,110,600 of property damage has occurred due to failure of natural gas transmission pipelines from 1986 to 2012 [49].

Due to an increasing number of incidents and their consequences, reliability of the pipeline system is becoming crucial for the operators and public in general. According to the statistics from PHMSA, from 2004 to 2013, the most common known cause of incidents in the US is due to corrosion (714 incidents, 25%), mechanical damage (339 incidents, 12%), human/operator error (279 incidents, 10%), material/weld/equipment failure (1056 incidents, 38%), natural hazard (174 incidents, 6%), sabotage/vandalism (96 incidents, 3%) and the rest of the causes (155 incidents, 6%) [49].

Due to the nature of the failure events, the frequency of failures and the related consequences, pipeline operators use their available funds more effectively for preventive maintenance actions. Maintenance helps the operators to use the resources more efficiently. Although the pipelines are designed, conducted, and operated correctly, deterioration occurs on the line internally or externally, directly or indirectly. Therefore, routine maintenance activities are crucial to keep the pipeline operation safe [46]. Maintenance policies help decrease the unexpected failures and reduce operational expenses. For example, Baker [50] emphasized that, although the failure pattern was consistent over time, the pattern was not affected by the aging of the infrastructure. Due to the this reason, Baker [50] did not observe any significant increase for pipeline failure from 1988 to 2008, due to the effectiveness of the industry efforts to control corrosion. Pipeline system reliability can be maximized and failure costs can be minimized with proper maintenance decisions [12].

The primary purpose of any pipeline system maintenance program is to maximize throughput and prolong the life of a pipeline system while ensuring public safety and respecting the environment [46]. Pipeline maintenance activities are planned activities such as monitoring, cleaning, CP, testing, patrolling, training, repair, and replacement [51]. For all types of systems, the manufacturer or operators prescribe maintenance schedules to reduce the risk of system failure [13].

Previous studies show that a significant number of maintenance actions are performed as corrective maintenance in pipeline systems [50]. The meaning of CM is that failures occur before measures are taken. Pipeline preventive maintenance determines the maintenance requirements by providing systematic inspection, detection and prevention of incipient failures [12]. Preventive maintenance requires a good knowledge of the pipeline characteristics, including whole variables that affect pipeline performance [46]. There are varieties of possible applications of PM policies [51]. Therefore, in the last several decades, a number of different preventive maintenance optimization models have been proposed to establish the optimal maintenance policies. Barlow and Hunter [52], Nakagawa (1981) [53], Valdez-Flores and Feldman [54], Wang [12], and Wang and Pham [55] surveys summarize the research and practice in reliability, maintenance, replacement, and inspection in different ways.

In the literature, there are two main replacement-types of preventive maintenance policies: age replacement and block replacement policies [51]. Age replacement policy means that the system is replaced when the system achieves an age equal to the policy age. The earliest age replacement policy considers that the system is replaced by a new one after each preventive maintenance. The policy considers renewal theory-based models for system performance. Therefore, systems are repaired to the "good-as-new" condition at each repair action due to renewal model assumptions. However, maintenance practice showed that a system or equipment continues to deteriorate even when the system or equipment was renewed. Although PM reduces failure probability, it does not restore the system operation condition to a "good as new" state. Therefore, renewal models are not suitable for many real systems [51].

As an alternative to renewal process, minimal repair models are proposed. The earliest minimal repair models were suggested by Barlow and Hunter [52]. According to Nguyen and Murthy [56], this model assumes that the system failure rate is not disturbed by any minimal repair of failures and the system is replaced at predetermined times. In other words, the minimal repair eliminates the failure but leaves the failure rate unchanged [57]. For pipeline systems, the failure rate increases with age; therefore, operation of the system would become increasingly expensive to maintain by minimal repairs. Thus, the main problem of the minimal repair models is when replacement actions are optimal instead of performing minimal repair [54].

Minimal repair models generally assume that: the failure rate function of the system increase, minimal repairs do not affect the system's failure rate,the cost of a minimal repair is less than the cost of replacing and system failures are detected immediately [54].

With the concepts of minimal repair and imperfect maintenance, these models were improved. These new established models are referred to as the age-dependent PM policy. This policy assumes that a system is preventively maintained at some predetermined age, or repaired at failure until a perfect maintenance is received [12]. Wang [12] noted that PM at the predetermined age and CM at each failure might be minimal, imperfect, or perfect. Therefore, many maintenance models are developed based on different types of PM (minimal, imperfect, perfect), CM (minimal, imperfect, perfect), cost structures, etc. [12]. On the contrary, if a system is repaired with only minimal repair at failure, the age replacement policy reduces to "the periodic replacement with minimal repair at failure" policy [12].

Periodic replacement policy is based on scheduled actions rather than on the system age. As is the case with age replacement policy, the earliest studies consider that the system is replaced by a new one after each preventive maintenance. However, with the concepts of minimal repair and imperfect maintenance, another PM periodic policy is established. This model is called "periodic replacement with minimal repair at failure" policy in which a system is replaced at predetermined times and failures are removed by minimal repair [12]. Also, this policy was introduced firstly by Barlow and Hunter [52]. Many extensions and variations are proposed for periodic replacement with minimal repair at failure policy. Nakagawa [53] studies four models of modified periodic replacement with minimal repair at failures. The first three models study a failure that occurs just before the replacement time is specified. The last model considers failure, which occurs well before replacement time. The last model suggests that the system is replaced at failure or at time, whichever occurs first.

The reviewed literature on pipeline system maintenance does not incorporate risks in maintenance. There is need to introduce the risk aspect into the maintenance these systems because of the unanticipated failures that occur during the operation of the pipeline systems.

2.5.1 Risk assessment of petroleum pipelines

Risk assessment is the study of probability and consequences of system failures. Oil and gas pipelines are vulnerable to the environment, and any leak and burst in pipelines have resulted in catastrophic accidents on human and marine lives [58].

Risk assessment also involves assessment of the likelihood that a given hazard will result in some consequences. Therefore, part of the risk assessment procedure is to qualitatively or quantitatively assess the level of risk that could emanate from an event.

Risk itself is a function of an event, its probability and associated consequences [59].

2.6 Review of Risk Assessment Methods

The concepts of safety and reliability were first introduced in aeronautical industry following the development of air transportation in the 1930s. Within this period the aircraft engineers were made to conduct careful studies of the statistical data on failure rates of aircraft components with the aim of achieving improvement in their design and accidents prevention. According to Bazovesky [60], this effort soon opened the way for a number of courses and books on safety and reliability analysis, as well as related statistical techniques.

The above development resulted in increasing the popularity level of the probabilistic safety and reliability analysis methods and eventual emergence of safety and reliability as a branch of engineering in the US where safety issues were accorded high priority in the 1950s, particularly in the aeronautical and nuclear industries. Also in focus within the period were the needs to study the impact of human error on these systems and how to prevent them. During the same period another milestone achievement by Watson led to the development of the fault tree concept for assessing the reliability of a system designed to control the Minuteman missile launch. This concept was further refined by Boeing Company leading to its extensive application to date [61]. In efforts to further complement this technique, failure mode, effects and criticality analysis (FMECA) was also developed in the early 1960s [62].

Further efforts were also intensified following a series of missile accidents and the growing public concerns regarding safety. The U.S. Air Force conducted several safety studies in order to ensure the adoption of system safety analysis in the aeronautics and nuclear industries. As a result, safety awareness soon attained essential status especially to the developers in hi-tech industries as such classification of potential accidents, in terms of frequencies of occurrence and consequences were considered in the design process on a 'right-first-time' basis. It also became clear that integrated studies were needed to detect and reduce potential hazards of large engineering products. Consequently, several standards regulating safety and reliability were developed and these efforts were similarly adopted in the UK [61].

In the mid 1960's, fuzzy sets theory was developed precisely in 1965 through the works of Lofti Zadeh who conceived many of its applications initially in the area of industrial controllers [63]. From this period onwards fuzzy sets and fuzzy logic witnessed a steady growth, it soon became a useful tool for application in other fields such as engineering, operational research, mathematics and most prominently in computer science [64].

Zadeh [65] stated that one of the basic aims of fuzzy logic is to provide a computational framework for knowledge representation and inference in an environment of uncertainty and imprecision. Since then fuzzy logic application continue to receive wider applications in the area of risk assessment due to its ability to effectively process information with some level of uncertainties. Fuzzy sets application in risk assessments are found in various works such as those by Kosmowoski and Kwesielewicz [66]; Richei et al [67]; Sii et al [68]; and Wang [69].

Yuhua and Datao [70] proposed a fuzzy-based approach to estimate the failure probability of oil and gas transmission pipelines using FTA. Expert elicitation and Fuzzy Sets Theory were used to get the probabilities of the basic events. However, the study unable to incorporate the uncertainty due to ignorance or lack of knowledge. Their work did not consider model uncertainty arises due to assumption of independence among basic events in FTA. Shahriar et al [71] in their study on "Risk analysis for oil and gas pipelines: A sustainability assessment approach using fuzzy based bow-tie analysis" aimed at helping owners of transmission and distribution pipeline companies in risk management and decision-making to consider multi-dimensional consequences that may arise from pipeline failures. The research results can help professionals to decide whether and where to take preventive or corrective actions and help informed decision-making in the risk management process.

In the 1970s, several innovations were adopted in order to advance industrial safety prediction methods. For example, in the nuclear power industries, accident scenarios were considered. These scenarios covered system failures and operator error during tests, maintenance, operations and reactor control. Following this development several new methods were developed including Event Tree Analysis (ETA). In addition, from the aeronautic industry emerged a Fault Tree Analysis (FTA) method which soon gained popularity and was adopted by other hi-tech industries. The Probabilistic Risk Analysis (PRA) methods were also developed for the evaluation of the performance and system maintenance [61].

In the 1980s, reliability, availability, maintainability and safety assessment techniques became widely adopted during the period, in efforts to control and manage major industrial hazards. This produced a distinct engineering discipline safety like others used in engineering design and involves concepts, measurable quantities and mathematical tools as well as methods for measuring and predicting these quantities according to Villemeur [72]. As designers began to rely more heavily on computers, greater numbers of analysis techniques (i.e. ETA and FTA) were incorporated into different codes of practice. Expert systems were also widely applied in combination with computerised assessment tools [61].

Also in the 1980s, Bayesian network was introduced. This method also deals with the mathematical modelling of expert opinions. Bayesian models have been applied in safety analysis for the assessment of rare events, such as catastrophic occurrence in complex technical systems [73]. This technique is used to process experts data to conduct a quantitative risk analysis (QRA) of rare events despite difficulties or lack of adequate failure information needed to compute relative frequencies.

In 1990s, the safety analysis advancements resulted in the inclusion of many more factors such as socio-technical and further studies towards the development of new mathematical models. The challenges at this time include the need to deal with uncertainties associated with the risk information which mathematical modelling can handle with great efficiency. Most of the mathematical based models developed within the period comprised of both the probabilistic and non-probabilistic [74].

2.7 Tools for risk analysis

2.7.1 Preliminary Hazard Analysis

The method was originally used by the US Army in the early 1960s, for the safety analysis of missiles and its use has since been extended to other fields. Following identification of hazards, its potential causes and consequences, possible preventive or corrective actions are tabulated.

Advantages:- Simple to use, fairly broad in scope and allows identification of hazards at an early stage. It can help the team of analysts to develop operating guidelines for application throughout the systems life cycle.

Drawbacks: - Preliminary studies need to be complemented by other studies to achieve the desired result. It is usually a precursor of other hazard analysis studies.

Related development: - PHA was further developed to include the rough estimates of the occurrence probability which is referred to as Preliminary Hazard & Risk Analysis (PHRA).

2.7.2 Failure Mode and Effect Analysis (FMEA)

According to the SAE standard J1739 [4], FMEA is defined as "a systematic procedure to evaluate potential failures, identify the effects of failures, and determine actions which could eliminate or reduce the chance of the potential failure occurring".

FMEAs are used across many industries and are often referred to by types such as System FMEA, Design FMEA (DFMEA), Process FMEA (PFMEA), Machinery FMEA (MFMEA), Functional FMEA, Interface FMEA and Detailed FMEA. Although the purpose, terminology and details can vary according to type and industry, the principle objectives of FMEAs are to anticipate the most important problems early in the development process and either prevent the problems or minimize their consequences. FMEA can be applied at any point in the product life cycle from the design to the end-of-life and provide a formal and systematic approach for product and process development [75].

The FMEA methodology is based on a hierarchical approach to determine how possible failure modes affect the system. The basic procedure is to [76]:

- Identify elements or functions in the system
- Identify all element or function failure modes
- Determine the effect(s) of each failure mode and its severity
- Determine the cause(s) of each failure mode and its probability of occurrence
- Identify the current controls in place to prevent or detect the potential failure modes
- Assess risk, prioritize failures and assign corrective actions to eliminate or mitigate the risk
- Document the process

For risk assessment, FMEA uses occurrence and detection probabilities in conjunction with severity criteria to develop a risk priority number (RPN). RPN is the product of severity, occurrence and detection. After the RPNs are evaluated, they are prioritized and corrective actions are taken to mitigate the risk. Once the corrective actions are implemented, the severity, occurrence and detection values are reassessed,and a new RPN is calculated. This process continues until the risk level is acceptable.

According to Signor [5], for failure prioritization in FMEA, a qualitative scale is transformed into a quantitative scale for evaluating RPN. Potential failure modes having higher RPNs are assumed to represent a higher risk than those having lower numbers. In the transformation of qualitative to quantitative scale all three indices, severity, occurrence and detection have the same metric and are equally important. Thus, small changes in one of the factors from which the RPN is computed can have different effects on the RPN.

Figure 2.3 is the FMEA life cycle [6].

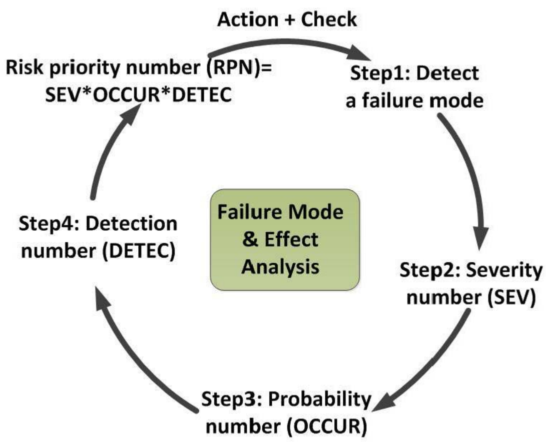

Figure 2.3: Life Cycle of FMEA

FMEA life cycle consists of series of steps; including calculation of severity, probability, detection, and RPN of risks which are basic findings for any FMEA implementation. RPN is the final measure for assessing risk in order to identify the critical failure modes associated with the process. Severity is an assessment of the magnitude of the potential effect of the failure, probability identifies the rate of likelihood that the failure

will occur, and finally detection identifies rate of likelihood that the problem will be detected before it reaches the end user. Rating scales normally range from 1 to 5 or from 1 to 10, where a higher number in this rating indicates higher risk.
The characteristic failure mode indexes are expressed on ordinal qualitative scales identifying the various levels of dangerous situations. Tables 2.2, 2.3 and 2.4 sourced from Stamatis [77], show the qualitative scales for the severity, frequency (Probability of occurrence), and the detectability indexes. All index scales used have the same number of scale levels, that is, from 1 to 10.

Table 2.2: Qualitative scale for severity index

Rating	Description	Criteria
1	No	No effect. No loss recorded.
2	Very slight	Very slight effect on equipment or system performance. Less than 0.50 m^3 loss.
3	Slight	Slight effect on equipment or system performance. Loss of 0.50 to 0.99 m^3.
4	Minor	Minor effect on equipment or system performance. Loss of 1 to 4 m^3.
5	Moderate	Moderate effect on equipment or system performance. Loss of 5 to 49 m^3.
6	Significant	Equipment performance degraded, but operable and safe. Partial failure, but operable. Loss of 50 to 99 m^3.
7	Major	Equipment performance severely affected but functional and safe. System impaired. Loss of 100 to 499 m^3.
8	Extreme	Equipment inoperable but safe. System inoperable. Loss of 500 to 999 m^3.
9	Serious	Potential hazardous effect. Able to stop equipment without mishap-time dependent failure. Compliance with government regulation is in jeopardy. Loss of 1000 to 4000 m^3.
10	Hazardous	Hazardous effect. Safety related-sudden failure. Non-compliance with government regulation. Loss greater than 4000 m^3.

Table 2.3: Qualitative scale for occurrence index

Rating	Effect	Criteria
1	Almost never	Failure unlikely. History shows no failure.
2	Remote	Rare number of failures likely. One occurrence in greater than fifteen years.
3	Very slight	Very few failures likely. One occurrence every twelve to fifteen years.
4	Slight	Few failures likely. One occurrence every eight to eleven years.
5	Low	Occasional number of failures likely. One occurrence every four to seven years.
6	Medium	Medium number of failures likely. One occurrence every two to three years.
7	Moderately high	Moderately high number of failures likely. One occurrence per year.
8	High	High number of failures likely. One occurrence every six months to one year.
9	Very high	Very high number of failures likely. One occurrence every three months.
10	Almost certain	Failure almost certain. History of failures exist from previous or similar designs. One occurrence per month.

Table 2.4: Qualitative scale for detectability index

Rating	Description	Likelihood of detection (Criteria)
1	Almost certain	Control will detect potential cause and subsequent failure mode.
2	Very high	Very high chance the control will detect potential cause and subsequent failure mode.
3	High	High chance the control will detect potential cause and subsequent failure mode.
4	Moderately high	Moderately high chance the control will detect potential cause and subsequent failure mode.
5	Moderate	Moderate chance the control will detect potential cause and subsequent failure mode.
6	Low	Low chance the control will detect potential cause and subsequent failure mode.
7	Very low	Very low chance the control will detect potential cause and subsequent failure mode.
8	Remote	Remote chance the control will detect potential cause and subsequent failure mode.
9	Very remote	Very remote chance the control will detect potential cause and subsequent failure mode.
10	Absolute uncertainity	Control cannot detect potential cause and subsequent failure mode.

2.7.3 Fault Tree Analysis(FTA)

A fault tree is a graphical model of the various combinations of faults that will result in the occurrence of undesired event. The faults can be events that are associated with errors and omissions or any risks which can lead to the undesired event. A fault tree thus depicts the logical interrelationships of basic events that lead to the undesired event which is the top event of the fault tree [78].

FTA lists all components of a system that are represented in a logical diagram showing the way their failures interact and result in an unwanted or undesirable event (top event). This technique uses deductive approach starting with top event like accident or incident. The main aim at this stage is to identify causes or initiating events and their logic combinations using "AND"/"OR" symbols of Boolean algebra [79].

FTA is a top-down approach to failure analysis, starting with a potential undesired event (problem) called a top event, and then determining all the ways it can happen. Rausand [80] states that FTA analysis proceeds by determining the causes of occurrence of the top event which will be connected through logic gates.

A fault tree may help to order information about an accident that has happened. The method is most suitable for technical (engineering) systems, although it allows the inclusion of human errors or organisational factors as basic or initiating events. Its uses can be classified as simple or complex depending on the system being analysed [78].

Lavasani et al [81] applied fuzzy fault tree analysis on oil and gas offshore pipelines. The study proposed a model that is able to quantify the fault tree of offshore pipeline system in the absence or existence of data. The study also illustrates with a case study the use of importance measures in sensitivity analysis. Zhong et al [82] applied FTA principle in the seismic secondary fires disaster of storage tanks. The study model was applied in the fires risk assessment of storage tanks after earthquake. It is helpful to assistant make decision in the earthquake prevention and disaster reduction works of cities.

The drawbacks to this method are that it can be costly and more time consuming, even when conducted with the aid of computer. A fault tree is not a model for all likely to occur in a system, it is rather a model of the interaction logic between events leading to the top event. The construction of the tree depends on the analyst's skills and ability to conduct the reliable analysis, as the analyst can miss some causes [78]. These weaknesses form major impediment against the application of this method in the current studies.

2.7.4 Event Tree Analysis (ETA)

An event tree is a graphical representation of mitigating or aggravating events that may occur in response to some initiating event or perturbation in the system. As the number of events increases, the picture fans out like the branches of a tree [83]. ETA techniques are helpful to identify the consequences that can result in the occurrence of a potentially hazardous event.

According to Muhlbauer [84] ETA is a logic sequence that graphically portrays the combination of events and circumstances in an accident sequence. It is an inductive method, which begins with an initiating undesirable event and works towards a final result (outcome); each branch of the Event Tree represents a separate accident sequence as stated by CCPS [85].

The uses of an Event Tree can be simple or complex depending on the system under analysis. It helps in the identification of control measures for reducing the harmful consequences of critical initiating events. Well suited for analysing events which can have several different outcomes.

The drawbacks of this method are that it does not describe the causes of the "intermediate events" in a clear manner. It can easily grow very large, and the analyst may never be sure whether all potential accident sequences have been identified. The construction of the tree depends on the analyst's skills and ability to conduct the analysis, as the analyst will require training. These weaknesses create major limitations for the application of this method in the current study.

2.7.5 Hazard Operability (HAZOP) Studies

This approach was developed in ICI Petrochemical Division in 1963 in the UK. The first published work on HAZOP was by Herbert G. Lawley [86] in 1974. This approach is generally considered to be "process industry" oriented, mostly used in the chemical, pharmaceutical and food industry. It uses simple guided words such as No/Not/None, More, Less, Reverse etc, to enable analysts find the deviation from the normality. It is also inductive and qualitative, and is presented in tabulated form.

This is a very useful method in identifying high hazards requiring further analysis and/or quantification, especially in the process industry. It can detect weaknesses early in the design stage.

The drawbacks to this method are that it is expensive and would require a large team of analysts to explore and it is time consuming as well. It is a complicated process of analysis.

Though this method is widely used in the oil and gas industry, the combination of the mentioned weaknesses and its reliance on expert assessment based on historical data without due regard for improvement in safety is considered to have a conservative approach towards consequence.

2.7.6 Root Cause Analysis (RCA)

RCA is a methodology employed to determine the most probable underlying causes of problems, complaints and undesired events within an organization, with the aim of formulating corrective actions to atleast mitigate, if not eliminate, those causes and so produce significant long term performance improvement [7].
RCA is used to address a problem or non-conformance, in order to get to the root cause of the problem. It is used so we can correct or eliminate the cause, and prevent the problem from recurring [87]. Figure 2.4 shows the RCA process [87]:

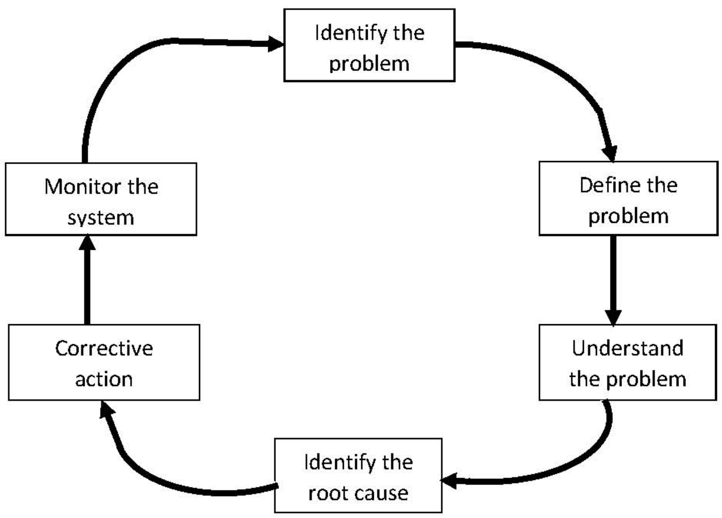

Figure 2.4: Root cause analysis process

The RCA process begins with the first step of Identifying the problem which involves describing the current situation and defining the deficiency in terms of the symptoms or indicators.
The second step is to define the problem whereby SMART (Specific; Measurable; Action oriented; Realistic; and Time constrained) principles are used. Unless the problem is defined accurately, the RCA whole process may be prone to failure.

The third step is on understanding the problem which involves obtaining real data regarding the problem, gaining a clear understanding of the issues. This is when the various tools and techniques, such as, cause and effect, brainstorming etc, can be used.
The fourth step is on identifying the root cause which involves analyzing the problem to identify the cause(s). Solutions to prevent recurrence of problems cannot be developed without identification of the root cause.
The fifth step is on the corrective action which entails determining and prioritizing the most probable underlying causes of the problem. Take corrective actions to at least mitigate or preferably eliminate the causes.
The RCA tools include 5 why's; pareto analysis; cause and effect diagrams; brainstorming/interviewing; process analysis, mapping and flowcharts. 5 Why's is sometimes referred to as Gemba Gembutsu (which literally means place and information in Japanese). The primary goal of the technique is to determine the root cause of a defect or problem by repeating the question "Why?". Each question forms the basis of the next question. The "5" in the name derives from an empirical observation on the number of iterations typically required to resolve the problem. No special technique or form is required but the results should be captured in a worksheet.
Pareto analysis technique uses the Pareto principle, i.e. the idea that by doing 20% of the work you can generate 80% of the advantage of doing the entire job. Pareto analysis is a formal technique for finding the changes that will give the biggest benefits. It is useful where many possible causes of action are competing for attention.
Cause and effect diagrams also known as fishbone diagrams (for their appearance) and Ishikawa diagrams (named after their developer Kaoru Ishikawa), is a technique used for more complex RCA's. This diagram identifies all the potential processes and factors that could contribute to a problem.
Brainstorming/Interviewing is a technique where ideas are collected from participants with no criticisms or judgments made while ideas are being generated. All ideas are

welcome no matter how silly or far out they seem.

Process analysis, mapping and flowcharts is an RCA tool where processes are mapped out by flowcharts. Flowcharts organize information about a process in a graphical manner thus making it clear what is impacted. Whether a problem has a documented process or not, this tool makes it easy to understand what is going on.

2.8 Tools for maintenance policy selection

The field of decision analysis has evolved a set of multicriteria decision making methods designed to improve both the decision making process and the quality of decisions made. Decision analysis tools include: Analytical Hierarchy Process (AHP), Decision Trees and Influence Diagrams.

2.8.1 Analytic Hierarchy Process

AHP was first developed by Saaty [8]. AHP is a theory of measurement through pairwise comparisons and relies on the judgements of experts to derive priority scales. The comparisons are made using a scale of absolute judgements that indicate how much more one element dominates another with respect to a given attribute [88].

AHP is also applied in petroleum pipeline maintenance. Nasir and Silvianita [89] applied AHP in prioritizing pipeline maintenance approach. In this study AHP was used to determine the risk factor for pipeline failure of two pipeline networks administered by different operators. The analysis of the pipelines showed that they all fell under low risk category. Dawotola et al [90] applied AHP in multi criteria decision analysis framework for risk management of oil and gas pipelines in Nigeria. The method prioritized oil and gas pipelines for design, construction, inspection and maintenance. In this study external interference was found to be the most prevalent failure factor. In order to reduce subjectivity, the accuracy of the severity of failure estimated could be further improved with more data from the pipeline operator.

Pipeline maintenance is an important aspect of the petroleum pipeline industry because of the correlation between maintenance with safe and failure-free operations. Historically, maintenance policies have been based on experience but current trends are toward a more organized, proactive methodology [91]. AHP provides a methodology for risk analysis, which, when applied to pipeline failure potential, creates a "cost-effective, customized, flexible, and logical maintenance plan" [91]. The focus of the hierarchy is the selection of an appropriate maintenance policy for the pipeline system which is the level I goal. The level II criteria include likelihood of corrosion, external interference, operational error, structural defects, or natural hazard [91]. Following the procedure for applying the analytic hierarchy process, level III entails the alternatives which are the maintenance policies.

Pipeline maintenance has traditionally been "hit or miss" or reactive due to the vastness of the systems. AHP, as applied to pipeline maintenance, offers a highly effective, proactive method of isolating areas of most likelihood for failure. There are two primary benefits for application of AHP in this research which would be applicable to any industry. AHP is a technique for the breaking down a complex problem with many factors by relating pairs of factors. In relating the factors, quantitative analysis and the subjective judgment of the decision makers can be connected.

There are three basic principles of AHP which include [92]:

(i) The principle of constructing hierarchies

A complex system is structured hierarchically by decomposing the elements into constituent parts according to essential relationships towards a desired goal which can make the whole system well understood [92].

(ii) The principle of establishing priorities

The first step in establishing the priorities of elements in a decision problem is to make pairwise comparison that is to compare the elements in pairs against a given criterion [92].

Table 2.5 shows the scale for pairwise comparison matrix [92]. Saaty [92] pointed out that experience has confirmed that a scale of nine units is reasonable and reflects the degree to which the intensity of relationships between elements can be discriminated.

Table 2.5: Scale for pairwise comparison matrix

Judgment	Explanation	Score
Equal importance of both elements.	Two criteria are of equal importance and equally contribute to the property or objectives.	1
Weak importance of one over another.	Experience and judgment slightly favour one criterion or element over another.	3
Essential or strong importance of one element over another.	Experience and judgment strongly favour one criterion or element over another.	5
Very strong and demonstrated importance of one element over another.	A criterion or element is strongly more important or favoured and its dominance is demonstrated in practice than the other.	7
Absolute importance of one element over another.	The evidence favouring one criterion over another is of the highest possible order of affirmation.	9
Intermediate values between adjacent scale values.	The intermediate values are used when compromise is needed.	2, 4, 6, 8

(iii) The principle of logical consistency

Logical consistency ensures that elements are grouped logically and ranked consistently according to a logical criterion. The consistency of the comparison matrix is monitored by an inconsistency ratio *(IR)* or consistency ratio *(CR)*. CR is calculated as follows [92]:-

$$CR = \frac{CI}{RI} \tag{2.1}$$

Where CI is the consistency index and RI is the Random index.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2.2}$$

Where 'n' is the number of criteria or sub-criteria of each level and λ_{max} is the largest eigenvector in the matrix.

Table 2.6 shows Random Index *(RI)* for consistency index of a randomly generated reciprocal matrix within a scale of 1 to 9 [92].

Table 2.6: Random index table

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

AHP is an effective method for dealing with complex decision making and can assist in identifying and weighing criteria, analyzing data collected and advancing the decision making process. AHP method has received considerable attention among decision makers and has demonstrated its applicability in different fields such as maintenance policy selection, prioritizing and selecting suitable organizational structure.

2.8.2 Decision trees

A decision tree is a graph that uses a branching method to illustrate every possible outcome of a decision [93]. It is a graphical representation of possible solutions to a decision based on certain conditions. It is called a decision tree because it starts with a single box (or root), which then branches off into a number of solutions, just like a tree.

Decision tree analysis applies to numerous decision making applications as an effective and useful tool in decision making. Haimes [93] broadens the concept of decision tree analysis to three categories of:

- Multiple noncommensurate, and conflicting objectives
- Impact analysis
- Analysis of extreme and catastrophic events

Decision trees are helpful, not only because they are graphics so you can see what you are thinking, but also because making a decision tree requires a systematic, documented thought process. Often, the biggest limitation of our decision making is that we can only select from the known alternatives. Decision trees help formalize the brainstorming process so we can identify more potential solutions.

2.8.3 Influence diagrams

Influence diagrams are a graphical alternative to decision trees. Decision nodes are represented by squares, chance nodes by circles, and outcomes by other shapes (typically octagons). Influence diagrams may be used to identify and to evaluate very complex decision networks.

2.9 Summary of literature

The findings and gaps identified from literature are as follows: -Chang et al. [31] proposed that risk can be expressed following a two-dimensional risk perspective, which is the product of the probability of failure and consequences. The study did not take into consideration the detectability aspect on the equipment under study.

-Hale et al [27] developed a theoretical model of an ideal maintenance management system incorporating safety. The study did not take care of incidents and breakdown analysis.

-Dalzell [28] recommended that risk is proportional to the square of the operating cost. The study did not incorporate other risk associated costs.

-Hu et al [29] proposed that Risk-based maintenance (RBM) strategy can be used in developing a cost-effective maintenance plan to make financial and safety improvements in a petrochemical system. It also proposed an improved RBM approach based on the proportional age reduction model. The results of this study showed that most equipment in this system are imperfectly repaired. The imperfect nature of the periodic preventive maintenance means it needs to be carried out more frequently.

-A study by Jo and Ahn [32] was useful for risk management during planning and building stages of a new pipeline and the modification of a burried pipeline. The research did not take an existing pipeline into consideration. -Han and Weng [33] proposed an integrated quantitative risk analysis method for natural gas pipeline network. The QRA results were a determination of individual risk and societal risk caused by different accidents. The study did not consider other risks associated with oil pipelines.

-Jo and Crowl [34] recommended that pipeline operators and regulators must address the associated public safety issues.

-Dey [36] in his study found out that this method could be used to prioritize the inspection and maintenance of pipeline segments. The study did not consider other pipeline system equipment.

CHAPTER THREE

3.0 METHODOLOGY

3.1 Introduction

In this chapter, the research methodology used in the study is described. The data collection and analysis tools and techniques are also described.

3.2 Study Area

The study was conducted at the Kenya pipeline company limited. The three pipelines under study are line I (Mombasa to Nairobi), line II (Nairobi to Eldoret), and line III (Sinendet to Kisumu). There are twelve (12) pump stations, seven (7) depots and a bifurcation station at Sinendet, which also forms part of this study. The major pipeline system equipment are: the pipeline, pumps, tanks, valves, mainline chamber valves, product loading equipment, strainers, pig hatches, and dump tanks. Figure 3.1 shows the pipeline system area under study.

Figure 3.1: Pipeline system area under study

3.3 Data collection

Data for the pipeline system was collected through maintenance records, safety and operations records, questionnaire and interviews. As a way of ascertaining the maintenance practices employed by the company, the research studied the maintenance records for the last sixteen years, i.e. 1998-2013.

To highlight the failures occurring in the pipeline system, statistical information regarding different failure scenarios were collected from product spillage, losses/pilferage/gains reports for the period. The reports captured the dates, incident details, location of incident, and the product volumes spilled and recovered. The reports were obtained from the safety and operations sections.

A questionnaire was also used to collect data for maintenance policy selection using

AHP. The expert questionnaire was issued to six engineers with over fifteen years experience in the pipeline system operation. The questionnaire was aimed at finding out the relative importance attached to maintenance policies with respect to criteria such as corrosion, structural defects, natural hazard, operational error and external interference. Failure based maintenance (FBM), condition based maintenance (CBM), time based maintenance (TBM) and design out maintenance (DOM) were the alternatives. For the purposes of this study unstructured interview method was used. Unstructured questions allow respondents to reply freely without having to select one of several suggested responses. The one-on-one, unstructured interview focused on: Identifying pipeline system equipment susceptible to failure, the controls in place to detect and mitigate risks, and suggestions on the improvements to the current risk mitigation measures.

In this study, six engineers drawn from maintenance, safety and operations departments were interviewed. These are the engineers that are directly involved in the running of the pipeline system equipment.

3.4 Data analysis

The data analysis tools and techniques used in this research are Failure Mode and Effects Analysis (FMEA) and risk matrix approach for risk identification and analysis, Root cause analysis (RCA) tools of cause and effect diagram and pareto charts for risk evaluation and analytic hierarchy process (AHP) for maintenance policy selection.

3.4.1 Application of Failure Mode and Effects Analysis

This research settled on the use of FMEA because, with this method of decision making, uniform quantification of risk can be applied, results can be correlated directly with

actual risks, the effects of various methods of mitigation/detection on risk can be modeled easily.It also provides a well-documented record of improvements from corrective actions implemented. FMEA provides information useful in developing in-line monitoring criteria, historical information useful in analyzing potential product failures, and it also provides new ideas for improvements. A successful FMEA helps identify potential failure modes, based on past experience with similar products or processes.
FMEA technique was applied in this research to identify risks and failure modes associated with the pipeline system. The technique utilizes Severity(S), Probability (P) and Detectability (D) indices to obtain a risk priority number (RPN) and a risk matrix graph that aid in ascertaining the level of risk.
The RPN is calculated by finding the product of the S, P and D values, thus:

$$RPN = S \times P \times D \tag{3.1}$$

The values for S, P, and D were obtained from tables 2.2, 2.3 and 2.4 respectively. Severity values were assigned from table 2.2 based on the product volumes lost as a result of pipeline system failure. In order to assign probability values, the number of incidents that have occurred for a particular equipment during the period under study was taken into consideration and the values obtained from table 2.3. Detectability values were assigned from table 2.4 based on the availability of the failure detection methods such as visual or audible warning devices, automatic sensing devices or sensing instrumentation.
A risk matrix is a graphical tool that combines the chance of occurrence of an event and the consequence. It is also a method of qualitative criticality analysis used to evaluate and prioritize activities which present risks. This was done by plotting the probability that the failure will occur on the Y-axis against the severity of the failure on the X axis. The risk matrices group the activities into the high, medium and low

risk groups. This illustrates which group of events requires attention to lower their potential risk but the method does not rank the items in decreasing value of threat as the RPN value method does. Where an activity lies on the grid in a risk matrix is based on two factors: severity and probability of occurrence.

3.4.2 Application of Root Cause Analysis

RCA was used in this study for risk evaluation. The benefits of RCA are that it uncovers relationships between causes and symptoms of problems and it also works to solve issues at the root itself and provides tangible evidence of cause and effect and solutions.

The RCA tools of cause and effect diagram (Ishikawa diagram) and pareto charts were used. The cause and effect diagram as shown in figure 3.2 was drawn to list out problems causing the failure of the pipeline system. The problems were categorized into eight main sections, namely internal corrosion, mechanical damage, equipment failure, construction/weld defect, external corrosion, sabotage/vandalism, human/operator error, and natural hazard. These sections formed the side bones leading to the center bone, which points towards the head representing the end effect "Pipeline system failure". Each side bone has secondary bones which represent the problems or the causes within the primary bone.

A Pareto chart was constructed in order to identify the major problem causing failure of the pipeline system. A pareto chart breaks a bigger problem into smaller pieces, identifies most significant factors and shows where to focus efforts. In order to construct the pareto chart, the pipeline system failure causes data was ordered from the most frequent occurring cause to the least frequent. A bar graph was plotted for each failure cause.

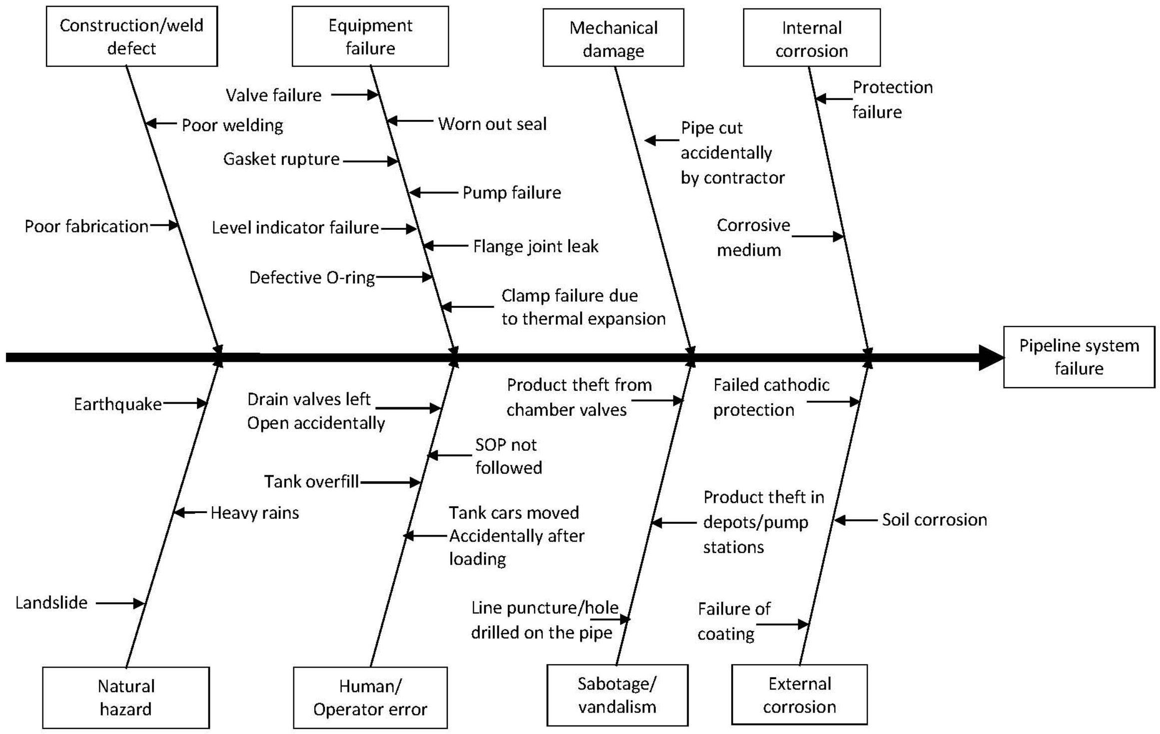

Figure 3.2: General cause and effect diagram

3.4.3 Application of Analytic Hierarchy Process

The AHP approach was used in this study for selection of maintenance policy. The advantages of AHP over other multi criteria methods are its flexibility, intuitive appeal to the decision makers and its ability to check inconsistencies. Additionally, the AHP method has the distinct advantage that it decomposes a decision problem into its constituent parts and builds hierarchies of criteria. AHP helps to capture both subjective and objective evaluation measures. While providing a useful mechanism for checking the consistency of the evaluation measures and alternatives, AHP reduces bias in decision making. The AHP method supports group decision-making through consensus by calculating the geometric mean of the individual pairwise comparisons. AHP is uniquely positioned to help model situations of uncertainty and risk since it is capable of deriving scales where measures ordinarily do not exist.

In this study the AHP approach used included outlining the problem, structuring the decision hierarchy, pairwise comparison of criteria (failure cause factors) and alternatives (maintenance policies), and determining priorities for the alternatives. The following steps outline the methodology used:

Step 1: Defining the study objective or goal

The objective of the study was to select an appropriate maintenance policy for the pipeline system.

Step 2: Identifying criteria for selecting maintenance policy

In this study, the criteria identified for maintenance policy selection are corrosion, structural defects, natural hazard, operational error and external interference. These are the factors attributed to the pipeline system failures.

Step 3: Determining the alternative maintenance policies

The maintenance policies used in this study were FBM, CBM, TBM, and DOM.

Step 4: Construction of a hierarchy framework for analysis

The criteria were structured into a hierarchy descending from the overall objective to the alternatives. The first level of the hierarchy represents the objective/goal, while the second level consists of the criteria (pipeline failure cause factors), the third level represents the alternative maintenance policies as illustrated in figure 3.3.

Step 5: Performing pairwise comparisons for each level of the hierarchy model

The pairwise comparison judgement matrices were obtained from the mean of the data collected through the expert questionnaire. The comparisons were entered in a pairwise comparison matrix. After developing the matrix, priority vectors or weights of the elements in the matrix were calculated, then the consistency ratios were determined. The consistency of the judgmental matrix was determined using equation 2.1 and 2.2: According to Saaty [92] a CR of 0.10 or less is considered acceptable, if the CR of the matrix is high, it means that the input judgments are not consistent and hence are not

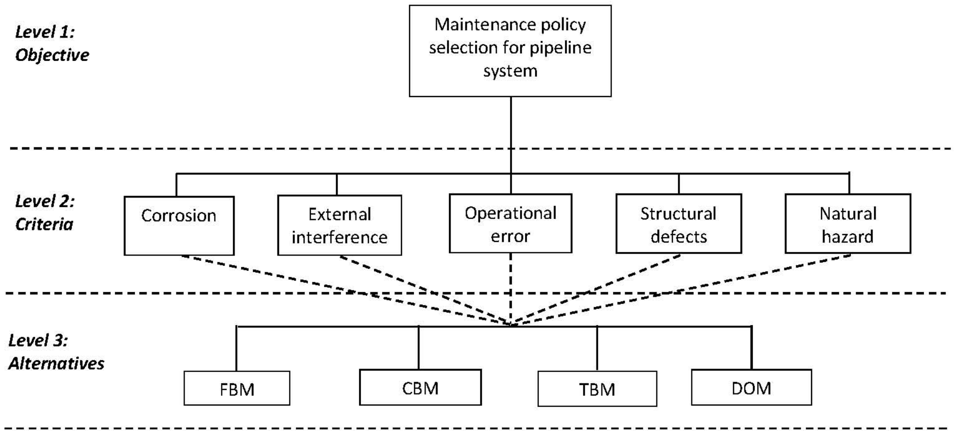

Figure 3.3: Maintenance policy selection model for pipeline system

reliable. Table 2.5 and 2.6 were instrumental in this analysis.

Step 6: Ranking of the alternatives (maintenance policies)

After calculating priorities for the criteria and decision alternatives, the ranking of the alternatives is calculated using equation 3.2:

$$P_j = \sum_{i=1}^{N} P_{j,i}.w_i \tag{3.2}$$

where P_j is the priority assigned to the alternative j; $P_{j,i}$ is the priority assigned to the alternative j for the criteria i; w_i is the priority assigned to the criteria i in respect to the goal.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Pipeline risk identification and analysis

The first objective of this research was to identify risks and to perform a risk analysis. Risk identification involves characterizing the various pipeline system incident/accident scenarios into their possible causes.

4.1.1 Summary of accidents for the pipeline system

Table 4.1 gives a summary of the pipeline system accidents that occured per pump station/depot/pipeline from 1998 to 2013. Details of these incidents/accidents are given in Appendix 2.

Table 4.1: Summary of accidents for the pipeline system from 1998 to 2013

Year	PS1	PS2	PS3	PS4	PS5	PS6	PS7	PS8	PS9	PS10	PS12	PS14	PS21	PS22	PS23	PS24	PS25	PS26	PS27	PS28	Line I	Line II	Line III	**Total**
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	**1**
1999	-	-	-	-	-	-	1	-	-	1	-	-	-	1	-	-	-	-	-	-	-	-	-	**3**
2000	-	-	1	-	-	-	-	1	1	-	-	-	-	-	-	-	-	-	-	-	1	-	-	**4**
2001	1	-	-	-	-	-	-	-	1	-	-	1	-	-	-	-	-	-	-	-	2	3	-	**8**
2002	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	1	-	-	5	1	**8**
2003	-	-	-	-	-	-	1	-	-	1	-	3	-	-	-	-	-	-	-	-	2	-	-	**7**
2004	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	1	-	-	**2**
2005	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	1	-	-	3	-	**5**
2006	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	1	-	1	-	**3**
2007	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	2	-	-	-	**3**
2008	-	-	-	-	-	-	-	-	2	-	-	2	-	-	-	-	-	-	-	1	-	-	-	**5**
2009	1	-	-	1	-	-	-	1	-	-	1	-	-	-	-	-	-	-	1	-	-	-	-	**5**
2010	-	-	-	-	-	-	-	-	2	-	-	-	1	-	-	-	-	-	-	-	-	1	-	**4**
2011	2	-	-	-	-	-	2	-	1	3	-	2	-	-	-	-	-	-	2	-	3	1	-	**16**
2012	-	-	-	-	1	-	1	-	1	-	2	1	-	-	-	-	-	-	1	-	1	2	2	**12**
2013	-	-	-	-	-	-	-	-	1	-	-	-	1	-	-	-	-	-	-	-	7	-	-	**9**
Total	**4**	**-**	**1**	**1**	**1**	**-**	**5**	**2**	**10**	**7**	**4**	**9**	**2**	**1**	**-**	**1**	**-**	**-**	**6**	**4**	**18**	**17**	**3**	**97**

From table 4.1, it is seen that PS2, PS6, PS23, PS25 and PS26 did not have any recorded incidents/accidents. PS3, PS4, PS5, PS22 and PS24 had one incident each. These were attributed to cases of human error and equipment failure. PS1, PS12 and PS28 had four incidents/accidents each. PS1 incidents were attributed to cases of human error/negligence and equipment failure, PS12 incidents were due to human

error/negligence, vandalism and equipment failure whereas PS28 incidents were attributed to human error and equipment failure. PS8 and PS21 had two incidents each and these were attributed to equipment failure. PS7, PS9, PS10, PS14 and PS27 had 5, 10, 7, 9 and 6 respectively. PS7 incidents were all attributed to equipment failure, PS9 incidents were attributed to product theft, construction/weld defect, human error/negligence, external corrosion and equipment failure. PS10 and PS27 incidents were due to human error and equipment failure whereas PS14 incidents were attributed to equipment failure, external corrosion, human error and product theft.
Line I and II had the highest number of incidents/accidents at 18 and 17 respectively attributed to rampant cases of vandalism. Line III had 3 incidents attributed to vandalism, mechanical damage and pipeline washout due to heavy rains (natural hazard).

4.1.2 Risks identified

Table 4.2 gives a summary of the identified pipeline system failure causes. In the table, the number of incidents attributed to a certain failure cause are indicated for each pump station/depot/pipeline.
It can be seen from this table that equipment failure had the highest number of incidents at 39. This could be attributed to the fact that equipment maintenance is only triggered after a failure has occurred or on routine maintenance. Thus, the maintenance for these equipment is not proactive. Natural hazard has the least number of incidents at only 1. This is because during the period under study, no major cases of natural calamities such as earthquakes and landslides have occurred. This one incident was attributed to a washout following heavy rains at line III (Km 106.2).

Table 4.2: Failure causes per pump station/depot/pipeline

Cause	PS1	PS2	PS3	PS4	PS5	PS6	PS7	PS8	PS9	PS10	PS12	PS14	PS21	PS22	PS23	PS24	PS25	PS26	PS27	PS28	Line I	Line II	Line III	**Total**
Internal corrosion	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	3	-	-	**4**
External corrosion	-	-	-	-	-	-	-	-	1	-	-	2	-	-	-	-	-	-	-	-	1	1	-	**5**
Mechanical damage	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	3	1	**5**
Sabotage/ Vandalism	-	-	-	-	-	-	-	-	1	-	1	1	-	-	-	-	-	-	-	-	8	12	1	**24**
Equipment failure	2	-	-	1	1	-	5	2	4	5	1	4	2	1	-	1	-	-	4	3	3	-	-	**39**
Human/ operator error	2	-	1	-	-	-	-	-	3	2	2	2	-	-	-	-	-	-	2	1	1	-	1	**17**
Construction/weld defect	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	1	-	**2**
Natural hazard	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	**1**
Total	**4**	**-**	**1**	**1**	**1**	**-**	**5**	**2**	**10**	**7**	**4**	**9**	**2**	**1**	**-**	**1**	**-**	**-**	**7**	**4**	**17**	**17**	**4**	**97**

Table 4.3 shows the causes of pipeline system failures for the period 1998 to 2013. The number of incidents attributed to each failure cause are indicated for each year.
In this table, it is seen that year 2011 recorded the highest number of incidents, most of which were equipment failure related. The least number of incidents were in 1998, the only reported incident was as a result of external corrosion.

Table 4.3: Annual causes of pipeline system failures

Cause	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	**Total**
Internal corrosion	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	3	**4**
External corrosion	1	-	-	-	-	2	-	-	-	-	-	-	-	-	1	1	**5**
Mechanical damage	-	-	-	-	-	-	-	-	-	-	-	-	1	2	2	-	**5**
Sabotage/ Vandalism	-	-	2	5	6	2	1	3	1	-	1	-	-	-	2	1	**24**
Equipment failure	-	2	1	1	1	2	-	1	2	1	3	3	2	11	4	4	**39**
Human/ operator error	-	1	1	1	1	1	1	1	-	2	1	2	1	2	1	-	**17**
Construction/weld defect	-	-	-	1	-	-	-	-	-	-	-	-	-	-	1	-	**2**
Natural hazard	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	**1**
Total	1	3	4	8	8	7	2	5	3	3	5	5	4	16	12	9	**97**

4.1.3 Frequency of occurrence of each cause of pipeline system failure

Frequency estimation involves determining the probability or likelihood of occurrence of an incident. The number of incidents occurring per failure cause divided by the the total number of incidents during the period under study gives the frequency of occurrence. Equation 4.1 was used in estimating the occurrence frequency of a given failure cause.

$$F = \frac{A_i}{T_i} \tag{4.1}$$

Where: F is the Frequency of occurrence; A_i is the number of annual incidents per failure cause; T_i is total number of incidents, annually.

Table 4.4 gives a summary of the number of incidents per failure cause and the frequency of occurrence.

Table 4.4: Pipeline failure causes

Failure cause	**Frequency**	**Percentage(%)**
Internal corrosion	4	4.12
External corrosion	5	5.16
Mechanical damage	5	5.16
Sabotage/ Vandalism	24	24.74
Equipment failure	39	40.21
Human/ operator error	17	17.52
Construction/ weld defect	2	2.06
Natural hazard	1	1.03
Total	**97**	**100.00**

From this table, it is seen that equipment failure is the most frequent factor at 40.21%, while natural hazard was the least frequent at 1.03%.

4.1.4 Annual product losses

Table 4.5 shows the annual product losses incurred by the company as a result of pipeline system failures. In this table, volumes lost for each cause of failure are indicated for each year.

It can be seen from this table that, the highest loss was recorded in 2013 with the organisation loosing 3061 m^3 of product. Year 2009 recorded the least loss of 5 m^3 attributed to incidents of equipment failure. Sabotage/vandalism led to the highest loss of 3732 m^3, which is due to the fact that when acts of vandalism occur, it takes time to arrive at the point of the incident and to mobilize resources to attend to the incident.

Table 4.5: Annual product losses by cause

Cause	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	**Total**
Internal corrosion	-	-	-	-	-	-	-	-	-	-	-	-	-	102	-	2680	**2782**
External corrosion	9	-	-	-	-	24	-	-	-	-	-	-	-	-	3	18	**54**
Mechanical damage	-	-	-	-	-	-	-	-	-	-	-	-	181	163	356	-	**700**
Sabotage/ Vandalism	-	-	862	880	639	306	18	188	579	-	-	-	-	-	30	230	**3732**
Equipment failure	-	6	87	21	-	4	-	3	30	16	6	5	4	35	9	133	**359**
Human/ operator error	-	48	18	1	8	-	1	104	-	2	1	-	-	43	3	-	**229**
Construction/weld defect	-	-	-	4	-	-	-	-	-	-	-	-	-	-	18	-	**22**
Natural hazard	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	-	**0**
Total volume	**9**	**54**	**967**	**906**	**647**	**334**	**19**	**295**	**609**	**18**	**7**	**5**	**185**	**343**	**419**	**3061**	**7878**

4.1.5 Risks associated with failure causes

To estimate the risk of a given risk/ failure factor, two items are required: the frequency of occurrence and the consequence. Equation 4.2 was used to generate table 4.6. The table shows the causes of pipeline system accidents, the frequency and consequence, the product volume lost and the risk in terms of the product volume lost per year.

$$Risk = F \times C \tag{4.2}$$

Where, F is the frequency (incidents/ year) and C is the consequence (Product volume lost/ incident).

Table 4.6: Risk estimates

Cause (A)	Incidents (B)	Frequency [Incidents/year] (C)	Consequence [Total Volume lost(m^3)] (D)	Volume lost/incident [m^3/incident] (E)	Risk [m^3/year] [(C)×(E)] (F)
Internal corrosion	4	0.25	2782	695.5	173.875
External corrosion	5	0.3125	54	10.8	3.375
Mechanical damage	5	0.3125	700	140	43.75
Sabotage/ vandalism	24	1.5	3732	155.5	233.25
Equipment failure	39	2.4375	359	9.2051	22.4374
Human/ operator error	17	1.0625	229	13.4706	14.3125
Construction/weld defect	2	0.125	22	11	1.375

In table 4.6, sabotage/ vandalism have the highest volume of fuel lost per year at 233.25 m^3 with construction/ weld defect having the least value of 1.375 m^3 per year.

4.1.6 Pipeline system equipment Failure Mode and Effects Analysis

Table 4.7 lists the pipeline system equipment prone to failure, their functions and cause of failure, failure mode and effect. The table also indicates the severity, probability, detectability and RPN values for each equipment.

From this table, it can be seen that the highest RPN value is that of mechanical damage and sabotage related effects to the pipe at 640. This is attributed to the high product volumes lost, high failure rates and the lack of failure detection facilities on the pipe. The RPN value for the dump tank is the least due to their close proximity to the operator and availability of failure detection equipment. Based on the RPN values, priority of attention is given to mechanical damage and sabotage, whereas dump tank related incidences will be given least attention.

In comparing RPN and risk matrix analysis, the results from the two tools tend to agree especially for high risk equipment. RPN analysis considers medium risk equipment in risk matrix analysis as low risk equipment.

Table 4.7: FMEA for pipeline system equipment

Item No.	Equipment name	Equipment function	Failure mode	Failure cause	Failure effect	S	P	D	RPN
1.	Pipe	Transport of petroleum Products.	-Pipe leak, rupture/burst.	-Mechanical damage and cases of sabotage.	-Product release/ spillage, possible fire/ explosion.	10	8	8	640
			-Corroded pipe	-Internal/ external corrosion.	Product loss, pipe damage, environmental effects, potential fire/ explosion.	9	6	8	432
			-Cracked weld	-High operating pressures, vibrations resulting from pigging exercise.	-Product release/ spillage, environmental effects.	5	4	8	160

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Table 4.7 – *Continued from previous page*

Item No.	Equipment name	Equipment function	Failure mode	Failure cause	Failure effect	S	P	D	RPN
2.	Pump	Transfer petroleum products through piping systems that come from one tank to another tank upstream.	Pump spill from vent linevia vent valve.	Pump suction pipe not completely filled with liquid, defective vent valve, running pump against a closed discharge valvewithout opening by-pass line.	-product loss, potential fire/ explosion, environmental effects.	5	6	6	180
3.	Strainer	-To protect downstream pipeline equipment by removing solids from a flowing fluid.	Fluid leaks/ spills from the top of the strainer.	-Cut O-ring, foreign material under the O-ring, strainer filled with debris.	-Spillage, potential fire/ explosion.	7	4	6	168

Continued on next page

Table 4.7 – *Continued from previous page*

Item No.	Equipment name	Equipment function	Failure mode	Failure cause	Failure effect	S	P	D	RPN
4.	Main tank	-Product storage.	-Product overflow.	-Faulty gauging system, operator negligence, high line operating pressures.	-Product spill, potential fire/ explosion.	5	4	7	140
5.	Flange joint	-To connect pipes, valves, pumps and other equipment to form a pipework system and to provide easy access for cleaning, inspection and modification.	-Product leak/ spill.	-Flange face leak, loose flange bolts, ruptured gasket, operating at pressures higher than recommended.	-Spillage, potential fire/ explosion.	7	6	8	336

Continued on next page

Table 4.7 – *Continued from previous page*

Item No.	Equipment name	Equipment function	Failure mode	Failure cause	Failure effect	S	P	D	RPN
6.	Accuload	-To accurately control batch loading of products through multiple loading arms.	-Product loaded into tanker exceeds assigned volume.	-Human error by inputting wrong volume, stop command not responding, telemetry failure.	-Product spillage/ loss, environmental hazard, potential fire/ tanker explosion.	5	6	7	210
7.	Chamber valves	-To prevent product back flow, pipe isolation in case of an emergency.	Product leak/ spill from the valve drain, equipment failure due to a defective gasket.	-Sabotage through product siphoning, equipment defect.	-Product spillage/ loss.	7	4	8	224
8.	Motorized valves	-To regulate, direct and control flow.	-Failed to operate (open/-close), valve leak.	-Valve seized, control system problem (communication faulty, software problem).	-Product spill, pumping stopped.	7	6	7	294

Continued on next page

Table 4.7 – *Continued from previous page*

Item No.	Equipment name	Equipment function	Failure mode	Failure cause	Failure effect	S	P	D	RPN
9.	Dump tank	Storage of mainline product from thermal and pressure relief valves, valve drains, strainer drains and seal leaks.	-Product overflow.	-Faulty gauge, faulty alarm system, product thermal expansion, strainer drain valve left open.	-Product release/ spillage, environmental effect, potential fire/explosion.	4	4	7	112

4.1.7 Risk matrix

Figure 4.1 shows the risk matrix for the pipeline system equipment failure. The frequency/ occurrence ranking of equipment failure is plotted on the Y-axis while the severity ranking based on volumes lost due to equipment failure is plotted on the X-axis. The matrix is derived from the rating, description and criteria of table 2.2 and 2.3. From the matrix, low risk starts from 1 to 5, medium risk starts from 6 to 7 and high risk is from 8 to 10.

From the risk matrix, it can be seen that high risk equipment are the pipe under the effects of mechanical damage, sabotage and corrosion, the flange joints and motorized valves. This is attributed to the high pressures in the pipeline that result into loss of large product volumes whenever an incident occurs.

In the medium risk category are pipe under the effects of a cracked weld, pumps, strainers, acculoads, chamber valves, dump tanks and main tanks. The incidents related to these equipment have not resulted into large product spills. None of the pipeline system equipment is low risk. This is due to the fact that even the slightest accident in a pipeline system may be catastrophic or lead to losses.

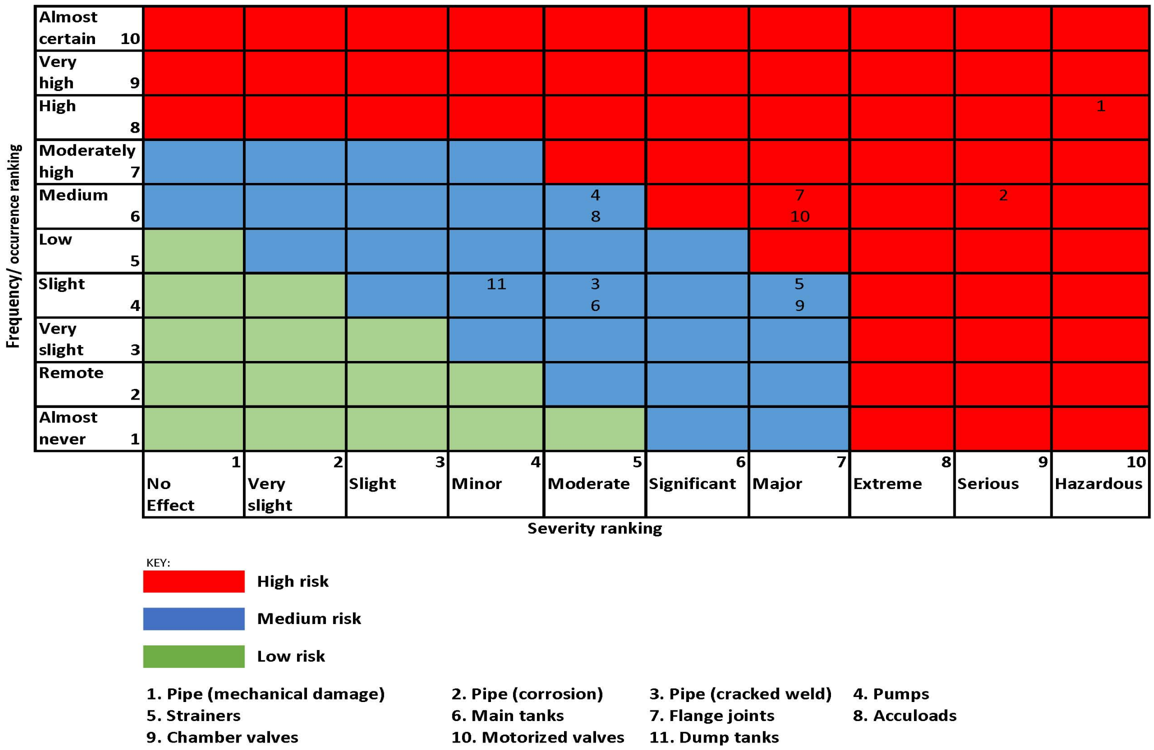

Figure 4.1: Pipeline equipment failure risk matrix

4.2 Risk Evaluation of the pipeline system

The second objective of this study was to evaluate the pipeline system failure risks. This is approached through root cause analysis tools of cause and effect diagrams and pareto charts.

4.2.1 Determining major causes of pipeline system failures

Figure 4.2 is a pareto chart showing the occurrence frequency and percent cumulative frequencies of the pipeline system failure causes. From the pareto chart, it can be seen that equipment failure and sabotage contribute 64.95% of the failure causes. Most of the incidents recorded during the period under study were due to equipment related failures. Sabotage was also common during this period which was attributed to product theft through drilling holes on the pipeline.

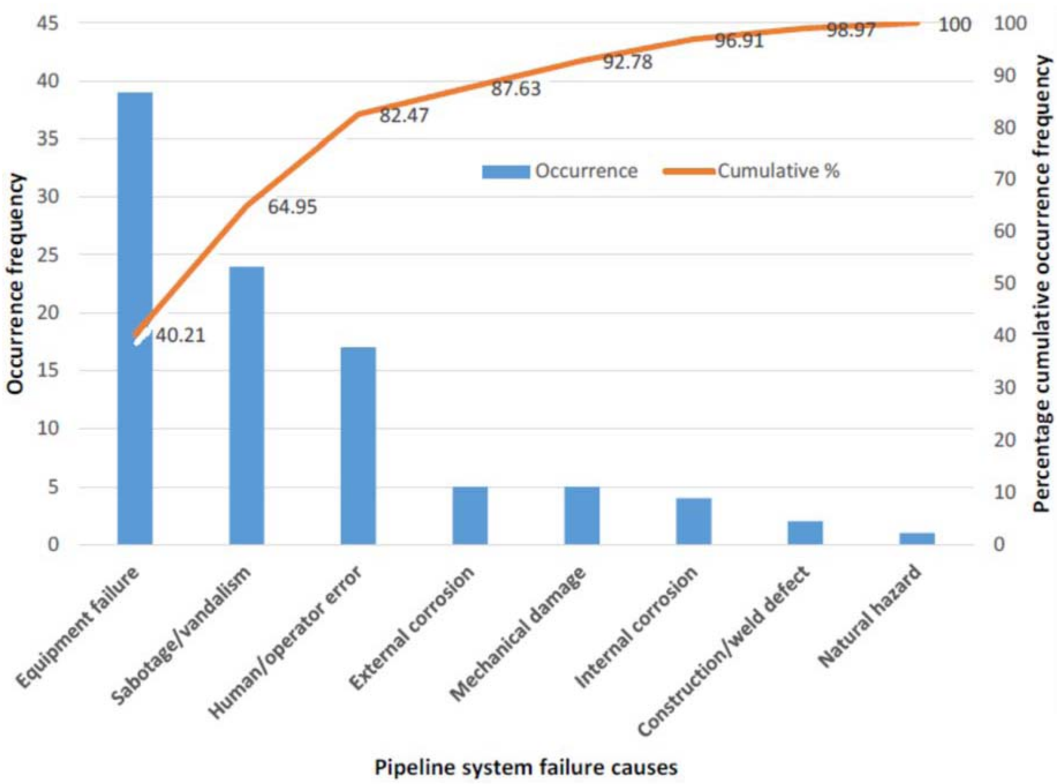

Figure 4.2: Pareto chart for pipeline system failure causes

Comparing the USA pipeline system incident data and that of Kenya for ten years from 2006 to 2013. Data in table 4.8 was used to generate figure 4.3 and 4.4. The difference in the occurrence frequency figures is attributed to the total pipeline length and the size of the system installations. The US has a total pipeline length of approximately 756,230 km while the Kenya pipeline has a total length of 1221 km.

Table 4.8: USA and Kenya pipeline system incident data (2006-2013)

Failure causes	Incidents in Kenya	Percentage	Incidents in the USA	Percentage
Corrosion	6	9	714	25
Mechanical damage	5	8	339	12
Human/operator error	11	17	279	10
Material/weld/Equipment failure	32	50	1056	38
Natural hazard	1	2	174	6
Sabotage/vandalism	9	14	96	3
All other causes			155	6
Total	64	100	2813	100

Figure 4.3 is a ten year (2004-2013) pareto chart for the Kenya pipeline system failure causes. In the ten year period, equipment failure and human/operator error were the major causes of pipeline system failure.

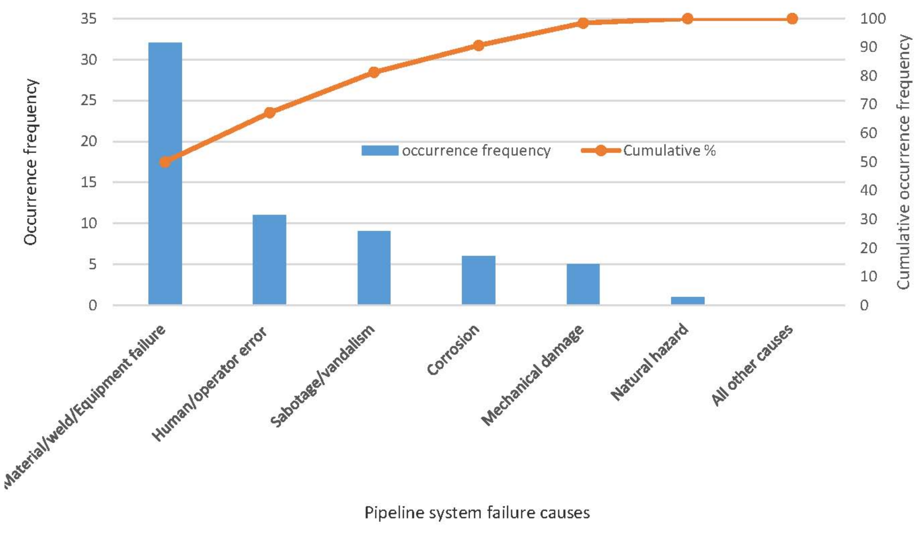

Figure 4.3: Pareto chart for Kenya pipeline system failure causes(2004-2013)

Figure 4.4 is a ten year (2004-2013) pareto chart for the United states pipeline system failure causes as derived from the data in the literature. In the ten year period, equipment failure and corrosion were the major causes of pipeline system failure. Equipment failure is a common major failure cause for both pipelines.

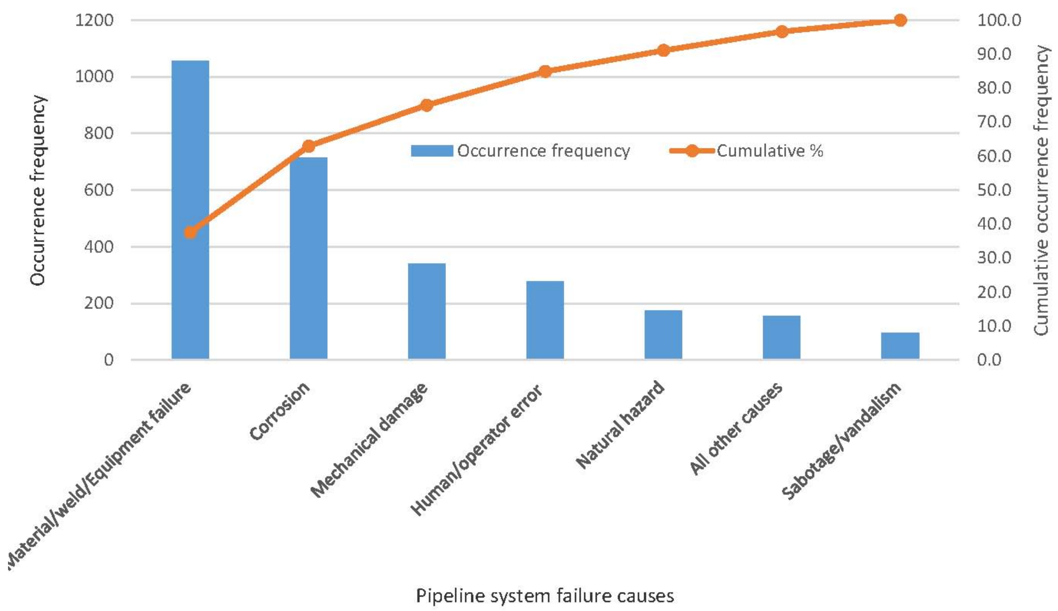

Figure 4.4: Pareto chart for US pipeline system failure causes(2004-2013)

4.2.2 Causes of equipment failure and sabotage/ vandalism

Figure 4.5 shows a cause and effect diagram for causes of equipment failure and sabotage/ vandalism. From this figure, it can be seen that the major causes of equipment failure are worn out seals, gasket rupture, defective O-ring, flange leak and valve failure among others. Acts of sabotage/ vandalism are as a result of product theft in depots/ pump stations and chamber valves and drilling holes on the pipeline. The table in Appendix 2 for details of pipeline system incidents/accidents from 1998 to 2013 was used in coming up with the causes of pipeline failure.

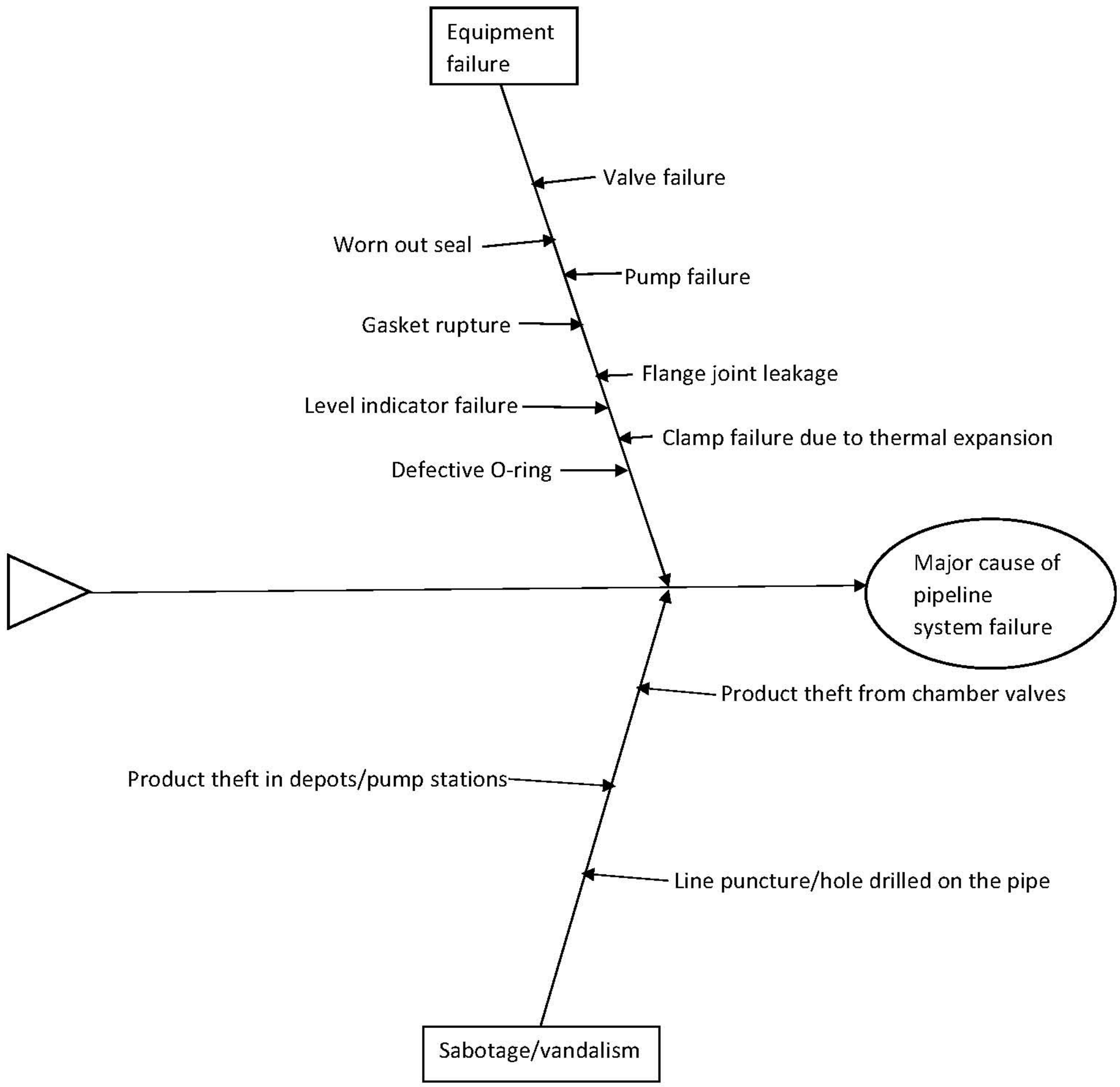

Figure 4.5: Cause and effect diagram of major pipeline system failure causes

4.3 Formulation of the framework for the selection of maintenance policy

The third objective of this study was on formulating a framework for maintenance policy selection. The goal is to provide a framework for selecting maintenance policies for the pipeline system. The AHP approach was used to achieve this objective. A questionnaire containing pairwise comparisons based on Saaty scale of decision preference was used to develop the AHP model. The steps followed in developing the AHP model were described in section 3.3.3.

4.3.1 Pairwise comparison of failure factors

A comparison matrix of the failure factors is generated from the average of the pairwise expert questionnaire responses. The responses are based on Saaty [8] scale of decision preference for comparing two failure factors. The scale is from 1 to 9, the intermediate numbers of 2, 4, 6, and 8 have not been included because they are only required when compromise is needed. The explanations for 1, 3, 5,7 and 9 are given below.

(1) Equally important

(3) Slightly important

(5) Strongly important

(7) Very strongly important

(9) Extremely important

The scale for expert judgment is as illustrated below.

Factor A	9	7	5	3	1	3	5	7	9	Factor B

We have five factors to make comparison, therefore, a comparison matrix of 5 by 5 is generated from the paired comparison. The diagonal elements of the matrix are always 1 and we only need to fill up the upper triangular matrix. The following rules were used to fill up the upper triangular matrix:

- If the judgment value is on the left side of 1, we put the actual judgment value.
- If the judgment value is on the right side of 1, we put the reciprocal value.

The following matrix was generated by comparing Corrosion, structural defects, natural hazard, operational error, and external interference.

Let A, B, C, D, and E represent Corrosion, structural defects, natural hazard, operational error, and external interference respectively.

$$
M= \begin{array}{c} \\ A \\ B \\ C \\ D \\ E \end{array}
\begin{array}{c} \begin{array}{ccccc} A & B & C & D & E \end{array} \\
\begin{pmatrix} 1 & 1 & 3 & \frac{1}{3} & 1 \\ & 1 & 3 & \frac{1}{5} & \frac{1}{3} \\ & & 1 & \frac{1}{5} & \frac{1}{3} \\ & & & 1 & 3 \\ & & & & 1 \end{pmatrix} \end{array}
$$

To fill the lower triangular matrix, the reciprocal values of the upper diagonal were used. Thus getting a complete comparison matrix as below.

$$
M= \begin{array}{c} \\ A \\ B \\ C \\ D \\ E \end{array}
\begin{array}{c} \begin{array}{ccccc} A & B & C & D & E \end{array} \\
\begin{pmatrix} 1 & 1 & 3 & \frac{1}{3} & 1 \\ 1 & 1 & 3 & \frac{1}{5} & \frac{1}{3} \\ \frac{1}{3} & \frac{1}{3} & 1 & \frac{1}{5} & \frac{1}{3} \\ 3 & 5 & 5 & 1 & 3 \\ 1 & 3 & 3 & \frac{1}{3} & 1 \end{pmatrix} \end{array}
$$

Having a comparison matrix above ,we compute priority vector, which is the normalized Eigen vector of the matrix. With the 5 by 5 reciprocal matrix from paired comparison, the sum of each column of the reciprocal matrix is calculated:

$$
M = \begin{array}{c} \\ A \\ B \\ C \\ D \\ E \\ SUM \end{array}
\begin{array}{c} \begin{array}{ccccc} A & B & C & D & E \end{array} \\
\begin{pmatrix}
1 & 1 & 3 & \frac{1}{3} & 1 \\
1 & 1 & 3 & \frac{1}{5} & \frac{1}{3} \\
\frac{1}{3} & \frac{1}{3} & 1 & \frac{1}{5} & \frac{1}{3} \\
3 & 5 & 5 & 1 & 3 \\
1 & 3 & 3 & \frac{1}{3} & 1 \\
\frac{19}{3} & \frac{31}{3} & 15 & \frac{31}{15} & \frac{17}{3}
\end{pmatrix} \end{array}
$$

Dividing each element of the matrix with the sum of its column, a normalized relative weight is gotten. The sum of each column is 1.

$$
M = \begin{array}{c} \\ A \\ B \\ C \\ D \\ E \\ SUM \end{array}
\begin{array}{c} \begin{array}{ccccc} A & B & C & D & E \end{array} \\
\begin{pmatrix}
\frac{3}{19} & \frac{3}{31} & \frac{3}{15} & \frac{5}{31} & \frac{3}{17} \\
\frac{3}{19} & \frac{3}{31} & \frac{3}{15} & \frac{3}{31} & \frac{1}{17} \\
\frac{1}{19} & \frac{1}{31} & \frac{1}{15} & \frac{3}{31} & \frac{1}{17} \\
\frac{9}{19} & \frac{15}{31} & \frac{5}{15} & \frac{15}{31} & \frac{9}{17} \\
\frac{3}{19} & \frac{9}{31} & \frac{3}{15} & \frac{5}{31} & \frac{3}{17} \\
1 & 1 & 1 & 1 & 1
\end{pmatrix} \end{array}
$$

The normalized principal Eigen vector was obtained by averaging across the rows,

$$
w = 1/5 \begin{pmatrix}
\\
\frac{3}{19} + \frac{3}{31} + \frac{3}{15} + \frac{5}{31} + \frac{3}{17} \\
\frac{3}{19} + \frac{3}{31} + \frac{3}{15} + \frac{3}{31} + \frac{1}{17} \\
\frac{1}{19} + \frac{1}{31} + \frac{1}{15} + \frac{3}{31} + \frac{1}{17} \\
\frac{9}{19} + \frac{15}{31} + \frac{5}{15} + \frac{15}{31} + \frac{9}{17} \\
\frac{3}{19} + \frac{9}{31} + \frac{3}{15} + \frac{5}{31} + \frac{3}{17}
\end{pmatrix}
$$

$$w = 1/5 \begin{pmatrix} 0.792 \\ 0.610 \\ 0.307 \\ 2.304 \\ 0.986 \end{pmatrix} = \begin{pmatrix} 0.159 \\ 0.122 \\ 0.061 \\ 0.461 \\ 0.197 \end{pmatrix}$$

The consistency check is done by obtaining the Principal Eigen value from the summation of products between each element of Eigen vector and the sum of columns of the reciprocal matrix.

λ_{max}=19/3(0.159)+31/3(0.122)+15(0.061)+31/15(0.461)+17/3(0.197)=5.252

Using equation 2.2,

Where λ_{max}=5.252 and n=5 (the size of comparison matrix)

Therefore, $CI = \frac{5.252-5}{5-1} = 0.063$

This Consistency Index (CI) is compared with Random consistency Index (RI). RI is obtained from the Random Consistency index Table 2.6.

Using equation 2.1,

if the value of Consistency Ratio is smaller or equal to 10%, the inconsistency is acceptable. If the Consistency Ratio is greater than 10%, the subjective judgment has to be revised.

From table 2.6, RI for n=5 is 1.12.

$CR = \frac{0.063}{1.12} = 0.0572$

The Consistency Ratio is 5.72%. This is less than 10% meaning that their is consistency.

Table 4.9 shows the results of the pairwise comparison of criteria used in the selection of the pipeline system maintenance policy. Corrosion, structural defects, natural hazard, operational error and external interference are the criteria used in the policy selection. In table 4.8, it can be seen that operational error is the most prevalent cause of pipeline failure with a priority vector of 0.461. Operational error is equipment failure or human error related. Operational errors occur during the operation of the pipeline and are basically human related, occurring due to the negligence or lack of knowledge on the equipment by the operator. Lack of standardized operating procedures, equipment malfunction or inadequate instrumentation may as well result to operational errors.

External interference is the second prevalent failure factor due to the fact that 29 mechanical damage and sabotage/vandalism cases have been reported during the period under study. Most of the mechanical damage incidents are due to interference from earth moving operations, particularly by earth digging excavators. Sabotage/vandalism incidents are due to line puncture and product theft attributed to lack of employment and economic backwardness on the part of the youth.

Corrosion is the third prevalent failure factor with a priority vector of 0.159. Corrosion attacks on pipeline are classified as either internal or external. Internal corrosion takes place within the walls of the pipeline whereas external corrosion attacks the surface of the pipeline burried on corrosive soil.

Structural defect related incidents are the fourth most prevalent failure factor. These defects occur mostly due to deformation in the pipeline material or as a result of construction defects that occur during the fabrication process. Material defects originate during the fabrication of the pipeline and may lead to metal loss and thinning of pipe walls. Construction defects are primarily scratches, gouges and dents which create avenues for corrosion attack due to the irregular surface or pores created which allow entrapment of air that react with water or moisture to form corrosion.

Natural hazard is the least prevalent failure factor. Natural hazard occurs as a result of heavy rains washout, landslide, lightning, earthquakes and other nature related calamities. During the period under study only one incident of a washout was reported which was attributed to heavy rains.

It can also be seen that the information contained in this table is consistent since it has a consistency ratio of 5.72% which is less than 10%. According to Saaty [8], data with a consistency ratio less than 10% is said to be consistent and vice versa.

Table 4.9: Results of pairwise comparison of failure factors

Criteria	Corrosion	Structural defects	Natural hazard	Operational error	External interference	Priority vector
Corrosion	1	1	3	1/3	1	**0.159**
Structural defects	1	1	3	1/5	1/3	**0.122**
Natural hazard	1/3	1/3	1	1/5	1/3	**0.061**
Operational error	3	5	5	1	3	**0.461**
External interference	1	3	3	1/3	1	**0.197**
Sum	**19/3**	**31/3**	**15**	**31/15**	**17/3**	**1.00**
CR=5.72%						

4.3.2 Pairwise comparison of maintenance policies with respect to failure factors (criteria)

i. Corrosion

The pairwise comparison of maintenance policies with respect to corrosion indicates that in order to reduce the number of failures of the pipeline system, priority is given to CBM. This entails performing maintenance based on the equipment condition. Failure based maintenance is the least prefered because running the equipment until it fails could be catastrophic and also costly to the organization as it could mean a major overhaul of the system. Table 4.10 illustrates this scenario.

Table 4.10: Pairwise comparison of maintenance policies with respect to corrosion

Maintenance policy	FBM	CBM	TBM	DOM	Priority vector
FBM	1	1/9	1/7	1/3	**0.050**
CBM	9	1	1	3	**0.418**
TBM	7	1	1	3	**0.393**
DOM	3	1/3	1/3	1	**0.139**
Sum	**20**	**22/9**	**52/21**	**22/3**	**1.000**
CR=0.39%					

ii. Structural defects

Table 4.11 illustrates the pairwise comparison of maintenance policies with respect to structural defects. From this table, it is seen that DOM is given priority with respect to structural defects. In order to avoid structural defects related failure, it is preferred that the equipment is redesigned and a completely new design is put in place.

Table 4.11: Pairwise comparison of maintenance policies with respect to structural defects

Maintenance policy	FBM	CBM	TBM	DOM	Priority vector
FBM	1	1/3	5	1/3	**0.164**
CBM	3	1	5	1	**0.368**
TBM	1/5	1/5	1	1/9	**0.050**
DOM	3	1	9	1	**0.418**
Sum	**36/5**	**38/15**	**20**	**22/9**	**1.000**
CR=5.34%					

iii. Natural hazard

Table 4.12 illustrates the pairwise comparison of maintenance policies with respect to natural hazard. Natural hazard was due to heavy rains resulting to a washout. The preferred maintenance policy for natural hazard is CBM because the maintenance on the pipe system has to be performed based on its condition at that particular moment. The least preferred maintenance policy is FBM because running the pipeline till failure may result into more catastrophic incidents that may lead to product losses and environmental degradation.

Table 4.12: Pairwise comparison of maintenance policies with respect to natural hazard

Maintenance policy	FBM	CBM	TBM	DOM	Priority vector
FBM	1	1/7	1/5	1/3	**0.057**
CBM	7	1	3	5	**0.588**
TBM	5	1/3	1	3	**0.263**
DOM	3	1/5	1/3	1	**0.122**
Sum	**16**	**176/105**	**68/15**	**28/3**	**1.000**
CR=6.57%					

iv. Operational error

Table 4.13 illustrates the pairwise comparison of maintenance policies with respect to operational error. From this table, it can be seen that CBM is the most prefered maintenance policy with a priority vector of 0.566. This is due to fact that in order to reduce equipment failures the condition of the equipment has to be monitored and maintenance action initiated based on the condition. FBM is the least preferred maintenance policy. This is because pipeline system equipment are very sensitive in terms of accidents that are bound to occur if they fail, therefore it would not be economical to run a pipeline equipment till it fails.

Table 4.13: Pairwise comparison of maintenance policies with respect to operational error

Maintenance policy	FBM	CBM	TBM	DOM	Priority vector
FBM	1	1/5	1/3	1	**0.101**
CBM	5	1	3	5	**0.566**
TBM	3	1/3	1	1	**0.201**
DOM	1	1/5	1	1	**0.132**
Sum	**10**	**26/15**	**16/3**	**8**	**1.000**
CR=4.34%					

v. External interference

Table 4.14 illustrates the comparison of maintenance policies with respect to external interference. The pairwise comparison of the maintenance policies gives preference to FBM. This means that external interference which is as a result of either mechanical damage or sabotage/vandalism initiates maintenance action based on the incident occurrence. Maintenance is immediately initiated at the occurence of an incident in order to reduce massive losses associated with these incidents.

Table 4.14: Pairwise comparison of maintenance policies with respect to external interference

Maintenance policy	FBM	CBM	TBM	DOM	Priority vector
FBM	1	3	7	5	**0.549**
CBM	1/3	1	5	5	**0.300**
TBM	1/7	1/5	1	1	**0.071**
DOM	1/5	1/5	1	1	**0.080**
Sum	**176/105**	**22/5**	**14**	**12**	**1.000**
CR=7.34%					

4.3.3 Priorities for the Maintenance policies

Table 4.15 illustrates the priorities for the maintenance policies. In this table, it can be seen that CBM is the most preferable maintenance policy with a priority vector of 0.467. This could be due to the fact that the use of CBM techniques ensures that maintenance is done based on the state of the equipment at a particular time. CBM approach also helps predict equipment failures and this therefore makes it suitable for the pipeline system.

DOM is the least preferred perhaps because it entails redesigning the system. Redesigning the system could be costly to the pipeline operator as it implies coming up with a new system.

From table 4.6, it can be seen that through corrosion (internal and external), structural defects(construction/weld), operational error (equipment failure and human error), and external interference (mechanical damage and sabotage/vandalism) the pipeline company looses 177.25 m^3, 1.375 m^3, 36.750 m^3, and 277 m^3 respectively in a year. By adopting CBM alongside the existing maintenance methods the company will be able to minimize these losses.

Table 4.15: Priorities for maintenance policies

Maintenance policy	Priority
FBM	0.187
CBM	0.467
TBM	0.191
DOM	0.157

4.4 Pipeline system risk based maintenance strategy

Based on this study, figure 4.6 shows the maintenance strategy for the pipeline system. For every risk factor, there is a proposed maintenance policy. The high priority maintenance policy that this study recommends for the pipeline system is the condition based maintenance.

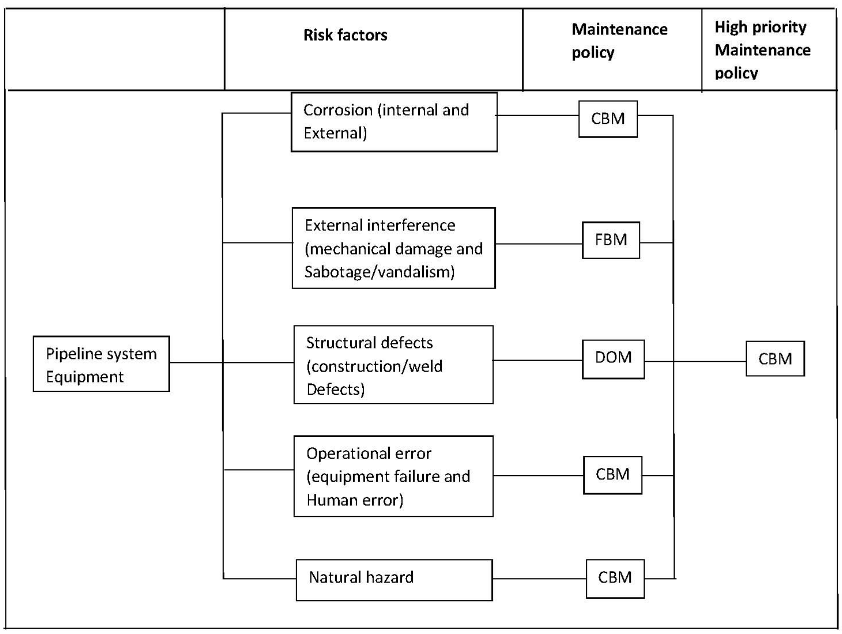

Figure 4.6: Maintenance strategy for the pipeline system

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, a risk based maintenance strategy for the multiproduct petroleum pipeline was developed. The main factors and sub factors leading to the pipeline system failures were identified using the available data at Kenya Pipeline Company Limited. Maintenance policy for the pipeline system was formulated based on the identified risk factors. The following are the main conclusions that can be drawn from this study:

1. The pipeline system failure risk factors are mainly operational errors, external interference, corrosion, structural defects and natural hazards.
2. The major causes of pipeline system failure are equipment failure and vandalism.
3. The contributors of equipment failure include valve failure, worn out seals, pump failure, gasket rupture, flange joint leaks, level indicator failure, clamp failure and defective O-rings.
4. The maintenance policies for each identified risk are: for corrosion, CBM; for structural defects, DOM; for natural hazard,CBM; for operational errors, CBM; and for external interference, FBM.
5. On overall, condition based maintenance is the most preferred maintenance policy for the pipeline system.

5.2 Recommendations

The present work did not consider the financial implications of the risks. In order to have a deeper understanding, the following recommendations can be made for future work.

- Investigate financial consequences arising from the pipeline system failures by developing a model that will combine all the consequences of failure.
- Determine the tolerable and acceptable risk levels for the pipeline system.

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APPENDIX A

A.1 Questionnaire

The information required and that will be provided by you in this document is strictly for research purposes and will be treated with confidentiality. The purpose of this questionnaire is to collect information to be used in selecting an appropriate maintenance policy for the pipeline system using analytic hierarchy process (AHP).

In case you have any querries on the questionnaire please feel free to contact,

Mark Ekeru Achilla, a master of science in mechanical engineering student at the Jomo Kenyatta University of Agriculture and Technology on:

Email-meachilla@yahoo.com or Mobile no. 0735748839 0r 0722482122.

A.1.1 IDENTIFICATION OF RESPONDENT

Respondent's name (optional)..

Title/position (optional)...

Telephone number (optional) ....

Email address (optional)...

A.1.2 SELECTION OF MAINTENANCE POLICY FOR THE PIPELINE SYSTEM

This questionnaire will be useful in selecting appropriate maintenance policy for the pipeline system. The responses are based on Prof. Saaty's scale of decision preference for comparing two attributes. The scale is from 1 to 9, the intermediate numbers of 2, 4, 6, and 8 have not been included because they are only required when compromise is needed. The explanations for 1, 3, 5,7 and 9 are given below.

(1) Equally important

(3) Slightly important

(5) Strongly important

(7) Very strongly important

(9) Extremely important

A.1.3 PART 1: PAIRWISE COMPARISON OF CRITERIA FOR MAINTENANCE POLICY SELECTION

Q1.Which would you rate more important between corrosion and structural defects?

Corrosion	9	7	5	3	1	3	5	7	9	Structural defects

Q2. Which would you rate more important between corrosion and natural hazards?

Corrosion	9	7	5	3	1	3	5	7	9	Natural hazard

Q3. Which would you rate more important between corrosion and operational error?

Corrosion	9	7	5	3	1	3	5	7	9	Operational error

Q4. Which would you rate more important between corrosion and external interference?

Corrosion	9	7	5	3	1	3	5	7	9	External interference

Q5. Which would you rate more important between Structural defects and Natural hazards?

Structural defects	9	7	5	3	1	3	5	7	9	Natural hazards

Q6. Which would you rate more important between Structural defects and operational error?

Structural defects	9	7	5	3	1	3	5	7	9	Operational error

Q7. Which would you rate more important between structural defects and external interference?

Structural defects	9	7	5	3	1	3	5	7	9	External interference

Q8. Which would you rate more important between natural hazards and operational error?

Natural hazards	9	7	5	3	1	3	5	7	9	Operational error

Q9. Which would you rate more important between natural hazard and external interference?

Natural hazard	9	7	5	3	1	3	5	7	9	External interference

Q10. Which would you rate more important between operational error and external interference?

Operational error	9	7	5	3	1	3	5	7	9	External interference

PART 2: PAIRWISE COMPARISON OF CRITERIA WITH RESPECT TO ALTERNATIVES

WITH RESPECT TO CORROSION

Q11. Which would you rate more important between FBM and CBM?

FBM	9	7	5	3	1	3	5	7	9	CBM

Q12. Which would you rate more important between FBM and TBM?

FBM	9	7	5	3	1	3	5	7	9	TBM

Q13. Which would you rate more important between FBM and DOM?

FBM	9	7	5	3	1	3	5	7	9	DOM

Q14. Which would you rate more important between CBM and TBM?

CBM	9	7	5	3	1	3	5	7	9	TBM

Q15. Which would you rate more important between CBM and DOM?

CBM	9	7	5	3	1	3	5	7	9	DOM

Q16. Which would you rate more important between TBM and DOM?

TBM	9	7	5	3	1	3	5	7	9	DOM

WITH RESPECT TO STRUCTURAL DEFECTS

Q17. Which would you rate more important between FBM and CBM?

FBM	9	7	5	3	1	3	5	7	9	CBM

Q18. Which would you rate more important between FBM and TBM?

FBM	9	7	5	3	1	3	5	7	9	TBM

Q19. Which would you rate more important between FBM and DOM?

FBM	9	7	5	3	1	3	5	7	9	DOM

Q20. Which would you rate more important between CBM and TBM?

CBM	9	7	5	3	1	3	5	7	9	TBM

Q21. Which would you rate more important between CBM and DOM?

CBM	9	7	5	3	1	3	5	7	9	DOM

Q22. Which would you rate more important between TBM and DOM?

TBM	9	7	5	3	1	3	5	7	9	DOM

WITH RESPECT TO NATURAL HAZARD

Q23. Which would you rate more important between FBM and CBM?

FBM	9	7	5	3	1	3	5	7	9	CBM

Q24. Which would you rate more important between FBM and TBM?

FBM	9	7	5	3	1	3	5	7	9	TBM

Q25. Which would you rate more important between FBM and DOM?

FBM	9	7	5	3	1	3	5	7	9	DOM

Q26. Which would you rate more important between CBM and TBM?

CBM	9	7	5	3	1	3	5	7	9	TBM

Q27. Which would you rate more important between CBM and DOM?

CBM	9	7	5	3	1	3	5	7	9	DOM

Q28. Which would you rate more important between TBM and DOM?

TBM	9	7	5	3	1	3	5	7	9	DOM

WITH RESPECT TO OPERATIONAL ERROR

Q29. Which would you rate more important between FBM and CBM?

FBM	9	7	5	3	1	3	5	7	9	CBM

Q30. Which would you rate more important between FBM and TBM?

FBM	9	7	5	3	1	3	5	7	9	TBM

Q31. Which would you rate more important between FBM and DOM?

FBM	9	7	5	3	1	3	5	7	9	DOM

Q32. Which would you rate more important between CBM and TBM?

CBM	9	7	5	3	1	3	5	7	9	TBM

Q33. Which would you rate more important between CBM and DOM?

CBM	9	7	5	3	1	3	5	7	9	DOM

Q34. Which would you rate more important between TBM and DOM?

TBM	9	7	5	3	1	3	5	7	9	DOM

WITH RESPECT TO EXTERNAL INTERFERENCE

Q35. Which would you rate more important between FBM and CBM?

FBM	9	7	5	3	1	3	5	7	9	CBM

Q36. Which would you rate more important between FBM and TBM?

FBM	9	7	5	3	1	3	5	7	9	TBM

Q37. Which would you rate more important between FBM and DOM?

FBM	9	7	5	3	1	3	5	7	9	DOM

Q38. Which would you rate more important between CBM and TBM?

CBM	9	7	5	3	1	3	5	7	9	TBM

Q39. Which would you rate more important between CBM and DOM?

CBM	9	7	5	3	1	3	5	7	9	DOM

Q40. Which would you rate more important between TBM and DOM?

TBM	9	7	5	3	1	3	5	7	9	DOM

Thank you for taking your time to answer the questionnaire.

APPENDIX B

B.1 Details of pipeline system incidents/accidents from 1998 to 2013

Table B.1: Details of pipeline system incidents/accidents from 1998 to 2013

Date	Incident/accident	Location	Cause	Effect
13.07.1998	-Spill at Nguzu river	-Line II Km219	-External corrosion	-Product spill and loss of 9.5 m^3
23.02.1999	-Tank side flange and pipework undergoing maintenance not blinded	-PS10	-Human error/negligence	-Product spill and loss of 48 m^3
29.05.1999	-Vent valve malfunction due to high operating pressures	-PS7	-Equipment failure	-Product spill and loss of 1 m^3
23.11.1999	-Product spill from strainer due to worn out seal	-PS22	-Equipment failure	-Product spill and loss of 5 m^3 -Fire
10.01.2000	-Product spill from station cascade system isolation ball valve	-PS8	-Equipment failure (Worn out spindle seals)	-Product spill and loss of 87 m^3
16.08.2000	-Line punctured by unidentified persons through chamber valve	-Line I (Km 352)	-Vandalism/Sabotage	-Product spill and loss of 852 m^3

Continued on next page

Table B.1 – *Continued from previous page*

Date	**Incident/ accident**	**Location**	**Cause**	**Effect**
20.11.2000	-Product lost and could not be accounted for.	-PS9	-Vandalism	-Product loss of 10 m^3
28.11.2000	-Product spill from an open suction valve left in an open position by maintenance personnel	PS3	-Human error	-Product spill and loss of 18 m^3
19.02.2001	-Spill of JET-A1 through ship(MT.HORIZON) storage tank vents	-PS14	-Equipment failure	-Product spill and loss of 21 m^3 -Water pollution
16.03.2001	-Line punctured	-Line II (Km 49.9)	-Vandalism	-Product spill and loss of 298 m^3
25.03.2001	-Line punctured	-Line II (Km 27.2)	-Vandalism	Product spill and loss of 203 m^3
14.05.2001	-Spill due to starting pump without following procedure	-PS1	-Human error/negligence	-Product spill and loss of 1 m^3
29.06.2001	-Spill due to a hole drilled on the pipe	-Line I (Km 318.46)	-Vandalism	-Product spill and loss of 246 m^3
18.09.2001	-Line puncture	-Line II (Km 222)	-Vandalism	-Product spill and loss of 31 m^3
26.09.2001	-Line punctured	-Line I (Km 335)	-Vandalism	-Product spill and loss of 128 m^3

Continued on next page

Table B.1 – *Continued from previous page*

Date	Incident/ accident	Location	Cause	Effect
05.11.2001	-Pipe joint burst at the hydrant area	-PS9	-Construction/weld defect	-Product spill and loss of 4 m^3
24.01.2002	-Line punctured	-Line II (Km 89)	-Vandalism	-Product spill and loss of 41 m^3
07.04.2002	-Spill due to main line pump recirculation line failure	-PS24	-Equipment failure	Product spill and loss of 0.1 m^3
12.04.2002	-Line punctured	-Line II (Km 28.8)	-Vandalism	-Product spill and loss of 25 m^3
18.06.2002	-Spill due to starting loading pump without following procedure	-PS27	-Human error	-Product spill and loss of 8 m^3
09.08.2002	-Hole drilled on the pipe by unknown persons	-Line II (Km 232)	-Vandalism	-Product spill and loss of 52 m^3
29.08.2002	-Line punctured	-Line II (Km 204)	-Vandalism	-Product spill and loss of 138 m^3
19.09.2002	-Line punctured	-Line III (Km 80)	-Vandalism	-Product spill and loss of 342 m^3
24.11.2002	-Line punctured	-Line II (Km 258)	-Vandalism	-Product spill and loss of 41 m^3
25.02.2003	-Spill from surge relief tank(10TK701)	PS10	-Equipment failure(sudden closure of outlet valve due to power failure)	-Product spill and loss of 4 m^3

Continued on next page

Table B.1 – *Continued from previous page*

Date	**Incident/ accident**	**Location**	**Cause**	**Effect**
14.05.2003	-MSP line rupture	PS14	-External corrosion	-Product spill and loss of 21 m^3
29.07.2003	-Valve malfunction	PS7	-Equipment failure	-Product spill and loss of 0.2 m^3
24.08.2003	-Pipe leak at tank farm area	PS14	-External corrosion	-Product spill and loss of 2.85 m^3
26.08.2003	-Tank 14TK1905 side valve left open	PS14	-Human error/negligence	-Product spill and loss of 0.001 m^3
10.10.2003	-Line punctured	Line I (Km 161.3)	-Vandalism	-Product spill and loss of 300 m^3
20.10.2003	-Line punctured	Line I (Km 38.6)	-Vandalism	-Product spill and loss of 6 m^3
06.01.2004	-Clamp fitted on the line to aid in product theft	-line I(Km 367.7)	-Vandalism	-Product spill and loss of 18 m^3
27.02.2004	-Spillage due to starting metering pump without following procedure	-PS9	-Human/operator error	-Product spill and loss of 0.6 m^3
06.09.2005	-Spill of MSP at the tank farm pump raft area	-PS27	-Equipment failure	-Product spill and loss of 3 m^3
14.09.2005	-Line punctured	-Line II (Km 99.5)	-Vandalism	-Product spill and loss of 125 m^3
22.11.2005	-Line punctured	-Line II (Km 211)	-Vandalism	-Product spill and loss of 26 m^3

Continued on next page

Table B.1 – *Continued from previous page*

Date	**Incident/ accident**	**Location**	**Cause**	**Effect**
10.12.2005	-Spill occasioned by lining up a strainer which was still under maintenance	-PS10	-Human error	-Product spill and loss of 105 m^3
29.12.2005	-Unknown persons drilled a hole on the line	-Line II (Km 203)	-Vandalism	-Product spill and loss of 38 m^3
02.02.2006	-Pipe punctured	-Line II (Km 38)	-Vandalism	-Product spill and loss of 579 m^3
13.08.2006	-Oil water separator pump breakdown	-PS28	-Equipment failure	-Product spill and loss of 15 m^3
07.10.2006	-Gasket rupture on the bypass line connecting line I and II	-PS10	-Equipment failure	-Product spill and loss of 15 m^3
14.05.2007	-Failure of the transfer pump to start either remotely or locally	-PS28	-Equipment failure	-Product spill and loss of 16 m^3
25.07.2007	-Edge of the loading island grazed by a loaded truck	-PS28	-Human error/negligence	-Product spill and loss of 2 m^3
15.11.2007	-Drain valve at tank farm area left open by maintenance personnel	-PS12	-Human error/negligence	-Product spill and loss of 0.4 m^3

Continued on next page

Table B.1 – *Continued from previous page*

Date	**Incident/ accident**	**Location**	**Cause**	**Effect**
07.02.2008	-Spill at the loading area	-PS9	-Human error	-Product spill and loss of 1.4 m^3
03.04.2008	-Failure of dispenser meters during truck loading	-PS9	-Equipment failure	-Product spill and loss of 0.49 m^3
02.05.2008	-Leakage from KOSF-KOT flange joint	-PS14	-Equipment failure	-Product spill and loss of 5 m^3
31.07.2008	-Hose pipe connected to the ship deck	-PS14	-Vandalism	-Product spill and loss of 0 m^3
13.10.2008	-Spill due to test done on PLC that was under maintenance	-PS28	-Equipment failure	-Product spill and loss of 0 m^3
15.01.2009	-Dump tank spillage	-PS12	-Human error	-Product spill and loss of 0 m^3
11.05.2009	-Failure to close by loaded truck valve	-PS27	-Equipment failure	-Product spill and loss of 3 m^3
23.05.2009	-Spill due to a partially open slop tank side valve	-PS1	-Human error	-Product spill and loss of 0 m^3
14.08.2009	-Spill through vent valves of both pumps (4P101 and 4P201)	-PS4	-Equipment failure	-Product spill and loss of 1.5 m^3

Continued on next page

Table B.1 – *Continued from previous page*

Date	**Incident/ accident**	**Location**	**Cause**	**Effect**
18.09.2009	-Failure of drain sequence of pump 8P101	-PS8	-Equipment failure	-Product spill and loss of 1 m^3
30.04.2010	-Spill from a loaded truck	-PS9	-Human error	-Product spill and loss of 0.25 m^3
28.06.2010	-Spill from vessel No.5 flexible rubber joint	-PS9	-Equipment failure	-Product spill and loss of 3 m^3
31.10.2010	-Spill due to dump tank high level alarm failure	-PS21	-Equipment failure	-Product spill and loss of 1 m^3
17.11.2010	-Line punctured by CPP contractor	-Line II (Km 125)	-Mechanical damage	-Product spill and loss of 181 m^3
24.05.2011	-Line punctured by CPP contractor	-Line II (Km 169.3)	-Mechanical damage	-Product spill and loss of 33 m^3
12.06.2011	-Manifold valve could not open during interface monitoring	-PS10	-Equipment failure(Ruptured gasket)	-Product spill and loss of 2 m^3
27.06.2011	-Line rupture due to sudden stoppage	-Line I (Km 38)	-Operational error	-Product spill and loss of 40 m^3
27.06.2011	-Line rupture	-Line I (Km 40)	-Internal corrosion	-Product spill and loss of 102 m^3
10.07.2011	-Valve leak at the tie in of line II and line IV	-PS10	-Equipment failure	-Product spill and loss of 2 m^3
27.07.2011	-Line punctured by contractor	-Line I (Km 24.8)	-Mechanical damage	-Product spill and loss of 130 m^3

Continued on next page

Table B.1 – *Continued from previous page*

Date	**Incident/ accident**	**Location**	**Cause**	**Effect**
09.08.2011	-Spill through pump 7P101 vent line	-PS7	-Equipment failure	-Product spill and loss of 1 m^3
12.09.2011	-Rupture of gasket at line I/line IV bypass line flange joint	-PS10	-Equipment failure	-Product spill and loss of 20 m^3
18.10.2011	-Clamped reinjection line gave in at the clamp due to thermal expansion	-PS14	-Equipment failure	-Product spill and loss of 0 m^3
21.10.2011	-Spill from vent valves V204 and V205	-PS7	-Equipment failure	-Product spill and loss of 2 m^3
01.11.2011	-MSP/MSR isolation valve gasket gave in	-PS10	-Equipment failure	-Product spill and loss of 2 m^3
02.11.2011	-Spill through an MSP valve that was not fully closed	-PS14	-Human/operational error	-Product spill and loss of 3 m^3
13.12.2011	-Loaded truck valve failed to close	-PS9	-Equipment failure	-Product spill and loss of 1.1 m^3
13.12.2011	-Spill at the reception area	-PS27	-Equipment failure	-Product spill and loss of 3 m^3
23.12.2011	-Booster pump failure	-PS1	-Equipment failure	-Product spill and loss of 1.7 m^3

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Table B.1 – *Continued from previous page*

Date	**Incident/ accident**	**Location**	**Cause**	**Effect**
28.12.2011	-Spill at the manifold area due to relief system failure	-PS1	-Equipment failure	-Product spill and loss of 1.4 m^3
29.03.2012	-Line punctured by Zhonghao contractors earth moving equipment	-Line III (Km 115)	-Mechanical damage	-Product spill and loss of 78 m^3
02.04.2012	-Spill through pump 7P202 vent valve V204 and drain valve V205	-PS7	-Equipment failure	-Product spill and loss of 2 m^3
17.05.2012	-Product theft	-PS12	-Vandalism	-Product spill and loss of 30 m^3
07.06.2012	-Line punctured by earth moving equipment	-Line II (Km 191)	-Mechanical damage	-Product spill and loss of 278 m^3
15.09.2012	-Pipeline washout due to heavy rains	-Line III (Km 106.2)	-Natural hazard	-Product spill and loss of 0 m^3
20.09.2012	-Loaded truck driver drove off without detaching the loading coupling	-PS27	-Human/operator error	-Product spill and loss of 2.5 m^3
28.09.2012	-Clamp gave in as a result of pigging vibrations	-Line II (Km 81.5)	-Construction defect	-Product spill and loss of 18 m^3
30.09.2012	-O-ring of the pig hatch gave in	-PS5	-Equipment failure	-Product spill and loss of 2 m^3

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Table B.1 – *Continued from previous page*

Date	**Incident/ accident**	**Location**	**Cause**	**Effect**
29.10.2012	-Coupler flow control handle failed to hold	-PS12	-Equipment failure	-Product spill and loss of o.892 m^3
05.11.2012	-Common suction header line flange joint gave in	-PS14	-Equipment failure	-Product spill and loss of 4 m^3
08.11.2012	-Spill from the line running from the depot to JKIA	-PS9	-External corrosion	-Product spill and loss of 3 m^3
14.11.2012	-Product theft from the line	-Line I (Km 198)	-Vandalism	-Product spill and loss of 35 m^3
12.01.2013	-Line rupture of 600mm length	-Line I (Km 174.5)	-Internal corrosion	-Product spill and loss of 2383 m^3
30.03.2013	-Line rupture of 40mm length	-Line I (Km 40)	-External corrosion	-Product spill and loss of 18 m^3
31.03.2013	-Spill due to a defective gate valve	-Line I (Km 5)	-Equipment failure	-Product spill and loss of 124 m^3
17.06.2013	-Line punctured by unknown persons	-Line I (Km 5 chamber)	-Vandalism	-Product spill and loss of 230 m^3
12.07.2013	-Valve gave in	-Line I (Km 5)	-Equipment failure	-Product spill and loss of 5 m^3
30.09.2013	-Line rupture	-Line I (Km 185.9)	-Internal corrosion	-Product spill and loss of 105 m^3
01.10.2013	-Burst from the hydrant pump area	-PS9	-Equipment failure	-Product spill and loss of 3 m^3
27.10.2013	-Dump tank overflow	-PS21	-Equipment failure	-Product spill and loss of 1 m^3

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Table B.1 – *Continued from previous page*

Date	**Incident/ accident**	**Location**	**Cause**	**Effect**
31.10.2013	-Flange gasket failure	-Line I (Km 40)	-Equipment failure	-Product spill and loss of 192 m^3