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Integrity Management In The Energy Sector

An Investigation of Oil & Gas Assets

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Global Manufacturing Management
Submission date: June 2017
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Abstract

The incessant oil and gas pipeline vandalization (sabotage) in developing nations like Nigeria has become a thing of serious concern which threatens both human and national security. Efficient oil and gas pipeline integrity management has been identified as a major way to reduce the rate of such incidents.
Taking only the lifecycle view of oil and gas pipeline management cannot fully account for the problem of oil and gas pipeline vandalization (sabotage) since this problem involves certain factors external to the oil and gas pipeline. To fully account for such problem, the stakeholder perspective which puts into consideration all factors external to the oil and gas pipeline will be adopted as well.

Different leverage points for systemic interventions in the oil and gas pipeline system will be investigated and one of such leverage points considers the stakeholders of the oil and gas pipeline system.
A risk analysis of oil and gas pipelines in the four Niger delta regions of Nigeria will be presented in a bid to strengthen the knowledge of the root cause of these pipeline failures while performance indicators will be developed as to help in the monitor of the integrity level of these oil and gas pipeline systems in the Niger delta region of Nigeria

Acknowledgements

This Thesis presented a unique learning ground and challenge to me and will not be complete without recognizing the untiring efforts of some persons who took it upon themselves to ensure that this work comes to completion.

My thanks go to the business development manager of Traceco Norge As, Tor Magnus Saevareide for his assistance when I needed guidance from the company. To Harald Rølseth for being indirectly involved in this thesis. For his readiness and willingness to assist in whatever form whenever he was called upon to do so even though he never saw the student. To Dr. Peter Okoh, for always making out quality time to assist in the areas of his specialization. Thank you, I so much appreciate your effort.

To my supervisor Cecilia Haskins. For being such a good guide from my specialization project to this thesis. Always giving room for me to bring in my ideas not minding the change in scope. Thank you, I appreciate.
To my family for their support and encouragements during this master program.
Most of all to God almighty for the gift of life.

Dedication

To the loving memory of my dad late Mr. Benneth Amaegbu Aronu. Ever green in our memory.

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List of abbreviations

AHP	Analytical Hierarchy Process
AIM	Asset Integrity Management
AT	Asset Integrity
BC	Before Christ
BE	Basic Events
B-2-B	Business-to-Business
CBM	Condition Based Maintenance
CMMS	Computerized Maintenance Management
CP	Cathodic Protection
CVCE	Confined Vapor Cloud Explosion
DEA	Data Envelopment Analysis
D-2-A	Digital-to-Analogue
D-2-D	Device-to-Devices
EGIG	European Gas Pipeline Data Group
ET	Event Tree
ETA	Event Tree Analysis
FBE	Fusion Bounded Epoxy
FL	Fuzzy Logic
FMEA	Failure Mode and Effect Analysis
FOS	Fiber Optics Sensor
FTA	Fault Tree Analysis
HAZ	Heat Affected Zone
HDPE	High -Density Polyethylene
ICT	Information and Communication Technology
IDEFO	Integrated Definition for Process Modelling
ILI	In-Line Inspection
IO	Integrated Operations

LCC	Life Cycle Cost
MFD	Mechanical Flow Diagram
MFL	Magnetic Flux Leakage
MNOC	Multinational Oil Companies
MOSOP	Movement for the Survival of the Ogoni People
MTTR	Mean Time To Repair
NNPC	Nigeria National Petroleum Cooperation
O&G	Oil and Gas
OM	Operation and Maintenance
OOS	Operation Organizational Structure
OSC	Onshore Support Centre
OTDR	Optical Radar Technology
PFD	Process Flow Diagrams
PIMP	Pipeline Integrity Management Program
PVC	Polyvinyl Chloride
SOIL	Secure Oil Information Link
UT	Ultrasonic Technology

1 Introduction

1.1 Problem Description and Background

The increase in asset integrity incidents has heightened attention to the integrity of assets in recent years (Wenman and Dim,2012; Ramasamy and Sha'ri, 2015; OGP, 2010). Asset integrity which is the ability of an asset to perform its required function effectively and efficiently whilst safeguarding life and environment (Chandima and Markeset, 2012) has become a subject of concern in recent years most especially in the energy sector which is characterized by its continuous flow process nature that has resulted in its adoption of highly complex and sophisticated assets (Bobi, 2014; Stevenson, 2012) whose failure results in catastrophic consequences to humans and the natural environment, hence the need for effective management of the integrity of such assets.

Pipelines which are considered to be the most favored mode of transportation of oil and gas in large quantities and whose network now out-numbers other transportation modes such as trucks/train (due to its cost effectiveness, convenience & land use efficiency, higher reliability, higher degree of safety & security and environmental friendliness over great distances) represents a greater portion in capital investment in the oil and gas sector (Kishawy and Gabbar, 2010) and so should be free from any form of degradation which could cause environmental hazards and potential threats to life.

The management of the integrity of pipelines whose fundaments lie in failure prevention, inspection and repair has become necessary in ensuring the longevity of such pipelines.

Many research that have been done on this area like Ramasamy and Sha'ri (2015); Qingfeng, et al. (2011); Kishawy and Gabbar (2010); Schuman and Brent (2005) all fully support the notion that effective management of the integrity of pipeline should take a lifecycle turn i.e. it should be focused on the different stages in the life cycle of an asset from the design stage through construction, operation, maintenance to the demolition stage of the asset which in this case is the pipeline.

Although, the life-cycle perspective is well applauded, it cannot properly account for the efficient management of some integrity threats like vandalization of pipelines, Pipeline sabotage, oil bunkering etc. which is most common in developing countries like Nigeria where there are social classes i.e. there are the very affluent people in the society and then the people living in abject poverty. This is because the lifecycle perspective focuses only on the system leaving out the socio-cultural aspect of the system in which the stakeholders are put into consideration. Going by the above premises, places to intervene in pipeline system otherwise known as the leverage points will be studied in this thesis. Leverage points are places within a complex system (a corporation, an economy, a living body, a city, an ecosystem) where a small shift in a subsystem results to a significant change in the entire system (Meadows, 1997). Such leverage points as identified in a pipeline system are (i) The design stage (ii)The operation and maintenance stage (iii) Pipeline monitoring and inspection (iv) The mindset or paradigm out of which the pipeline arises

This thesis will investigate the different ways of ensuring the integrity of oil and gas pipelines. The author focuses attention on the most critical oil-producing region of Nigeria (the Niger delta region). A context diagram of this problem domain is depicted in figure 1.

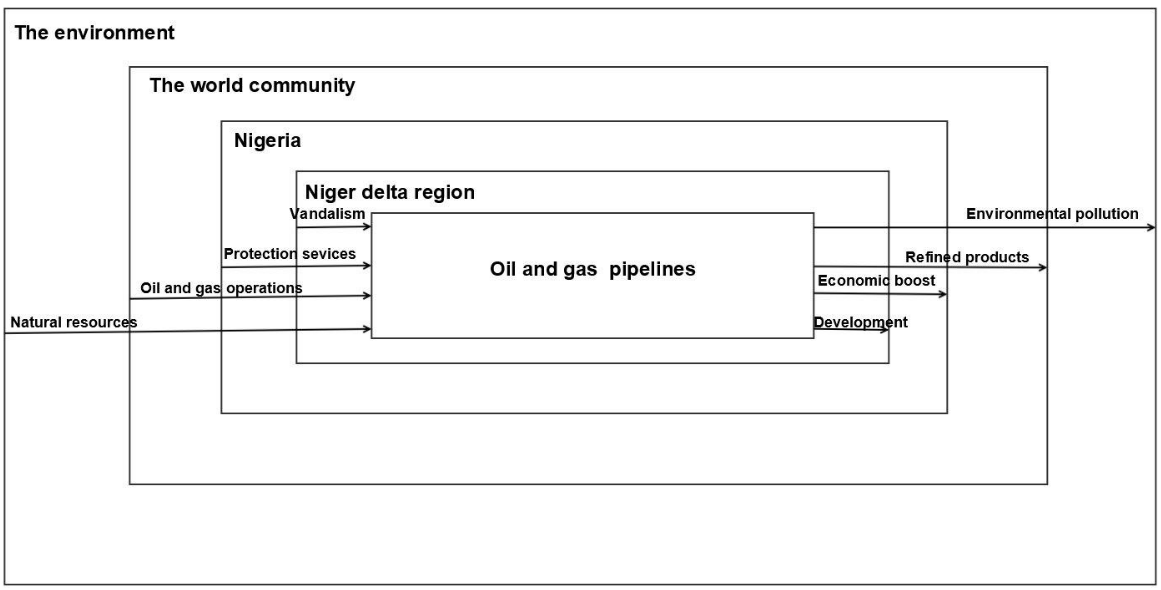


Figure 1: The context diagram of the problem domain

The thesis proceeds as follows: Chapter 2 gives the Research Methodology. Chapter 3 gives the Theory and Literature Studies. Chapter 4 gives the Results and Analysis. Chapter 5 gives the Discussion and Conclusion.

1.2 Research Objectives and Questions

This work aims at establishing the most effective way to monitor/manage oil and gas pipelines. After series of literature searches it was discovered that a lot of research have been done on the lifecycle perspective of oil and gas pipeline management which entails managing the integrity of pipelines from the design stage through operation and maintenance stage to the demolition stage. But such perspective cannot fully account for some integrity threats like pipeline sabotage (oil bunkering), pipeline vandalization etc. as experienced in some developing nations because the lifecycle perspective concentrates only on the system (the pipeline) leaving out the stakeholders which are the more contributive factors to the mentioned threats.

To achieve the said objective, places that needed interventions otherwise known as leverage points were studied with the necessary interventions given to such places. To ensure that the integrity level at such places does not fall below the allowable threshold or exceed a certain level, integrity indicators were developed to monitor the level of the integrity at such points.

The objectives of this research are to establish an effective way to monitor/manage the integrity of oil and gas pipelines since the lifecycle perspective cannot fully account for oil bunkering, pipeline vandalization that is often experienced in developing nations. This is hoped to be achieved by:

- Identifying the various leverage points for systemic change in an oil and gas pipeline system.
- Effecting those systemic changes in the identified leverage points most especially the highest leverage point.

To achieve the above objectives, the following research questions were formulated.

RQ1. What are the major systemic risks to pipelines?

RQ2. What methods are appropriate to address the integrity of pipelines during the delivery phase of the oil and gas sector?

RQ3. What indicators can support risk frameworks used to secure pipeline delivery system?

1.3 Research Scope

This research took an extensive look at the various threats to the integrity of pipeline and discovered that some threats have not been fully accounted for by the popular lifecycle perspective. While seeking solution to this problem, both the system view of the pipeline and the stakeholder view were taken. In the system view, the various condition based maintenance methods for oil and gas pipelines were explored as a solution to effect systemic change in one of the leverage points while Integrated Operations was introduced as the solution to effect systemic change in another leverage point.

The stakeholder perspective was adopted in the last leverage point to take one out of the system domain for one to be able to explore other factors external to the system that threatens the integrity of pipelines. Such factors were identified with the respective interventions given to those areas.

1.4 Research Limitations

The major limitation of this research comes from the fact that most of the information used were from literature studies, interviews and newspapers. There was no empirical evidence to back up these information as used in this research. A case study would have helped to deepen the knowledge since literature studies are a bit different when it comes to life experience.

Pipeline data collection from oil and gas companies was extremely difficult because the companies did not want to release information about their activities. The few companies that tried to publish some of their data falsified them to protect their interest.

2. Research Methodology and Approach

2.1 Overview of research

This section aims at presenting the background for the specific research approach that was adopted for this master thesis.

Research according to (Brown, Suter and Churchill 2013), is a systematic way of fact discovery and interpretation to increase knowledge.

Research methods, which are all methods/techniques that are used for the conduction of research, differs from research methodology, which is a way of systematically solving a research problem (Kothari, 2004). Such methods encompass scientific research and research in the humanities. Scientific research method was adopted for this thesis and it entails the principles and procedures for the systematic pursuit of knowledge involving the recognition and formulation of a problem, the collection of data through observation and experiment, the formulation and testing of hypothesis.

Different classifications of research were given by Kothari (2004), but the classification used for this research is the classification according to the quantifiability of data. By this classification, research is broadly categorized into:

- Quantitative: This is based on the measurement of quantity or amount and is mostly applicable to phenomena that can be expressed in terms of quantity. It is also seen as the systematic empirical investigation of any phenomena through statistical, mathematical or computational technique (Given, 2008).

- Qualitative: This relates to quality or kind and aims at discovering the underlying motives and desires using in depth interviews for the purpose (Kothari, 2004). According to Saunders (2011), it also deals with phenomena that are difficult or impossible to quantify mathematically such as meanings, beliefs, attributes, symbols etc.

Although these two are separate approaches to research, they arguably go hand in hand as asserted by Kuhn (1961) with qualitative research supporting quantitative research. In such case, it is called mixed method (Creswell and Tashakkori ,2007).

2.2 Research Content of this Master Thesis

2.2.1 Application of Scientific Methodology to this Thesis

Scientific methodology as seen by Ringdal (2001) are the different plans and techniques that are used to answer research questions. The first of such techniques that was adopted for this research to be able to answer the different research questions was intensive literature search into the different ways of managing assets efficiently. After series of thorough searches, it was discovered that the life-cycle perspective for asset management (i.e. from design, through operation and maintenance stage to disposal stage) has been mostly researched and well applauded by many authors. This was related to oil and gas assets and in this case, the oil and gas pipelines. Although the life-cycle perspective is a good approach to the management of oil and gas facilities, it failed to fully address some integrity threats like sabotage that is experienced in some developing countries, since this is more from external influence (pipeline stakeholders) and not from the system itself. More literature searches revealed that there has not been researches done connecting the life-cycle perspective with the stakeholder perspective of pipeline management.

This led to the adoption of exploratory research approach, which according to Brown, Suter and Churchill (2013) is used for the understanding of unclear situation where one strives to connect different factors in order to get more insight and ideas. Some of such exploratory (or qualitative methods) as used for this thesis are literature studies, interviews and discussions with the university supervisor, failure mode and event analysis (FMEA), data collection and analysis etc. These methods are further explained below:

- Literature Studies

Literature studies are cost and time effective method of obtaining a theoretical overview and the current situational understanding of the subject being studied, (Brown, Suter and Churchill, 2013). Literature search was helpful to this thesis by:

a. Allowing for the familiarization and understanding of the different pipeline management researches that have been done by other researchers

b. Opening some other areas that have not yet been explored by other researchers as long as pipeline management is concerned.

c. Increasing the credibility of this thesis.

Before embarking on these searches, a critical review of this thesis was done by generating research questions and the objectives of the thesis as presented in section 1.2. These were adopted after series of discussions and possible brainstorming with the supervisor. Some articles from key authors and recent reviews in this research were visited, this led to the adoption of keywords or search terms which according to Bell (2014) are the basic terms that describe the research question(s) and objective(s). The key words are as presented in table 1.

Table 1: Keywords used for literature search

Key words			
Level 1	Level 2		Level 3
Asset, Management, Risk, Integrity, Asset management, Reliability management, Integrity management, Risk management, Sustainability management.	Pipeline integrity	Pipeline risks	Nigeria
	Lifecycle, life cycle cost, Threats	Risk analysis, qualitative, quantitative, event tree, fault tree	Pipeline security, pipeline maintenance, pipeline stakeholders.

In order, not to reduce the standard that has been set by the previous researchers who have worked on this area, special care was taken to use more recent scientific papers as advised by the research supervisor. According to her, the papers to be used should not be more than five years old. As much as possible this was strictly adhered to but there were some situations where the older papers offered more information than the newer papers, in such cases, the older papers were adopted during the literature search.

Google scholar, Oria, Scopus and Web of science were the search engines used with Google scholar being the most used followed by Oria. While Web of science was often referred to for quicker scan through the abstract, google scholar gave easy access to the number of citations received by a paper.

- Interview

Purposeful discussions between two or more people also known as interviews (Kahn and Cannel, 1957) were used to gather reliable data (information) for this research. Structured interviews, which entail the use of standardized questions for the research participant(s) (Kothari, 2004), was conducted for the systems manager of Traceco company, Norway. Traceco company offers integrity services for oil and gas pipelines mainly through inspection. The interview was conducted through email and was aimed at gathering information needed for the development of integrity performance indicators for the operation and maintenance stage of the oil and gas pipeline which is one of the leverage points that was studied in this research.

In-depth interview also known as qualitative research interview (King, 2004) was used to explore in depth, the failure factors of oil and gas pipelines common in the different states of Nigeria and their probabilities of occurrence. This face-to-face interview was conducted for one of the oil and gas pipeline experts in NTNU who has experience with pipelines in Nigeria. His local knowledge of Nigeria pipelines helped in the development of the fault tree and the assigning of probabilities to the different pipeline failure factors.

- Meetings and Discussions with the research supervisor

It was agreed with the research supervisor from the beginning of this thesis that, meetings will be held every fortnight. During such meetings, the status of the research work is evaluated with possible feedbacks given while brainstorming was used to generate ideas in situations that needed some changes. Impromptu meetings were scheduled in-between, depending on the urgency of the matter while email messages were the most used mode of communication when the research supervisor was not readily available. These helped the work process to be more efficient while ensuring that updated information about the thesis existed between the student and the research supervisor.

- Failure Mode and Effect Analysis (FMEA)

FMEA which is a technique used to identify, prioritize and eliminate potential failures from a system, design or process before they reach the customer (Omdahl, 1988) was used in this research to identify all potential failure modes in oil and gas pipelines in Nigeria and eliminating them before they occur while identifying their possible effects.

This was achieved by carrying out a bow-tie analysis of the oil and gas pipelines in the four different states of Nigeria. The bow-tie analysis consisted of two basic parts (Shahriar ,Sadiq and Tesfamariam, 2012): (1) The Fault tree part which identified all the possible failure modes of oil and gas pipelines in Nigeria and their respective probabilities of occurrence (2) The event tree part which pointed out the consequences of such failure should they occur.

- Data Collection and Analysis

To be able to develop the failure probabilities of the different factors that threaten the integrity of pipelines in the Niger delta region of Nigeria, pipeline incident data were collected for four different states in this region. These incident data were collected from Nigeria national daily newspapers because the oil and gas companies could not release their incident data. These failure data were collected from 1999 (when democracy was returned to Nigeria) till date. They were analyzed to ascertain their possible root causes. From there, the failure probabilities were assigned to the different failure factors as presented in table 4. To ensure the correctness of these data (failure probabilities), the data were further confirmed by two experts who have knowledge with oil and gas pipelines in the Niger delta region of Nigeria.

2.3 Structure of Thesis

This structure of this research is as presented in table 2.

Table 2: The structure of thesis

Chapter 1 Introduction	This chapter begins with the problem description and background and proceeded to the research objectives and questions, the research scope and finally ended with the research limitations.
Chapter 2 Research Methodology and Approach	This chapter took an extensive overview of research and finally ended up describing the research used for this thesis.
Chapter 3 Theoretical foundation	This chapter explored the lifecycle view of asset management. Integrity threats were studied and foundation for integrity indicators were also laid. It ended up with an in-depth study of the four leverage points for systemic change.
Chapter 4 Results and Analysis	This chapter begins by carrying out risk analysis of oil and gas pipelines in the Niger delta region. Bow-tie diagram was used for the analysis and consists of the fault tree part and the event tree part. Failure probabilities of pipelines in this region were developed and the relative ranking of such probabilities were done in this chapter. The event tree specified the different consequences of oil and gas pipeline failure was developed.
Chapter 5 Discussions and Conclusion	This chapter begins by answering the research questions that were presented in chapter one, continued with section summary and ended with drawing the overall conclusion of the thesis.

3. Theoretical Foundation

This chapter in a bid to lay foundation for the work done in this research takes an extensive look at the various work that have been done in asset management with special focus on the lifecycle (system) perspective or view which is the most researched view in this area. It went further to explore the various integrity threats to oil and gas pipelines. The various leverage points for system change were identified here and systemic changes were made in this leverage points. The chapter ended up while taking the stakeholder perspective as a solution to the last leverage point.

3.1 Evolution of Asset Management

The development of physical assets can be traced back to (the ancient times) to the city of Ur whose citizens use wheels for their horse-propelled Wagons (Hastings, 2010). For such to have happened in those days, it simply means that there had been artisans who were familiar with the bearings on which the wheels depend and there could have existed as well those who were familiar with Lathe and other wood-working and metal-working tools that were needed to build the wagon. This also invariably means that some form of developed system of manufacture, maintenance and logistics must have existed in those times. Figure 2, is a picture that presents horse-propelled wagons that use wheels as were developed by the military of the city of Ur in 2600 BC.

Figure 2: Military assets – City of Ur 2600 BC (Hastings, 2010)

With this early beginning, one expects to see asset management as a well understood concept, instead the management of physical assets has never been well-understood by mankind because education and professional specializations have generally by-passed the physical asset management field, which resulted to the various technical fields adopting their own approach to the topic under different headings. In the same vein, asset management is often considered as the last option to be used to maximize cost savings in a competitive global economy due to its complexity especially in the developing nations Schuman and Brent (2005).

3.1.1 Asset management defined

Asset management has been in existence for long, only undergoing name-changing games which often leads to the assignment of various definitions to the concept. Davies (2007) defined asset management as a continuous-process improvement strategy for improving the availability, safety, reliability and longevity of plant assets i.e. systems, facilities, equipment and process etc. while Brown and Humphrey (2005) defined it in terms of cost and the risks it poses to a corporate organization. According to their definition, asset management is simply a corporate strategy that seeks to balance performance cost and risk. They went further to state that such balance requires the alignment of corporate goals, management decisions and technical decisions. In their terms, the goals of asset management are: (1) To balance cost performance and risk (2) To align corporate objectives with spending decisions (3) To create a multiyear asset plan based on rigorous and data-driven processes.

The more accepted definition takes a life cycle-perspective of an asset. In such definition, asset management is the life cycle management of physical assets to achieve the stated output of the enterprise (engineersaustralia.org). With this definition, asset management means keeping the asset in good operating condition till its end of life while for the yet-to-acquire-asset, it means applying sound technical and financial judgement in deciding the asset to be acquired to suit the business needs, acquiring such asset and logistically sustaining it over its entire life through to disposal (Lei, 2012).

Asset management is the systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for achieving its organizational strategic plan (PASS 55-1, 2008).

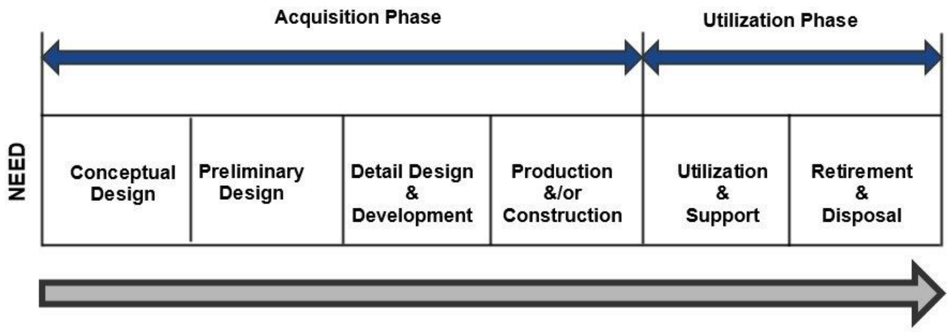


Figure 3: The asset life cycle (Blanchard & Fabrycky,1998)

From these definitions, it means that focusing asset management towards the life cycle of asset is central to achieving an organization's success and it's quite different from just an organizational ownership and maintenance of an asset. In other words, for an organization to gain greater value from their assets, the management process should extend from design, procurement and installation through operation, maintenance to retirement (Schuman and Brent, 2005). Simply put, it should take the life cycle perspective as presented in figure 3.

3.2 Asset lifecycle

The life cycle of an asset which is the economic life-time of an asset (Gram and Schroeder, 2012), consists of two phases as presented in figure 3.

(1) Acquisition phase: In this phase, the projections, purchasing, installations and commissioning of the assets are done based on the investment needs. The provision and installation of asset is done to either create additional production capacity or replace worn-out or over-aged asset, this can also be achieved by investing in new technology.

(2) Utilization phase: The beginning of this stage marks the useful stage of the asset during which it functions as it is expected but at the same time, the asset depreciates and this invariably reduces the productivity of the asset. To continuously keep the asset in good working condition, maintenance practices which could range from monitoring, attendance to repair are adopted to ensure that the equipment is kept in good working condition.

The continuous usage of the asset drives it to its retirement or disposal stage. At this stage the asset dissolves away from the operating process and tends towards its end-of-life due to the continuous depreciation in both value and operating condition. Keeping the equipment in good working condition no longer becomes economical and it is wise to disinvest or dispose the asset. Asset disinvestment reasons are not only due to the technical condition (abrasion of) assets but could also be due to economic reasons like changing demands, ensuring competitiveness, financing. etc.

Schumen and Brent (2005), in their work towards improving asset maintenance performance in the process industry identified the life-cycle approach to asset management as a method to not only improve the performance and productivity of an asset to the process industry but also as a means of reducing the operating and maintenance (OM) cost of an asset. The life of an asset begins with the identification of the need of the asset.

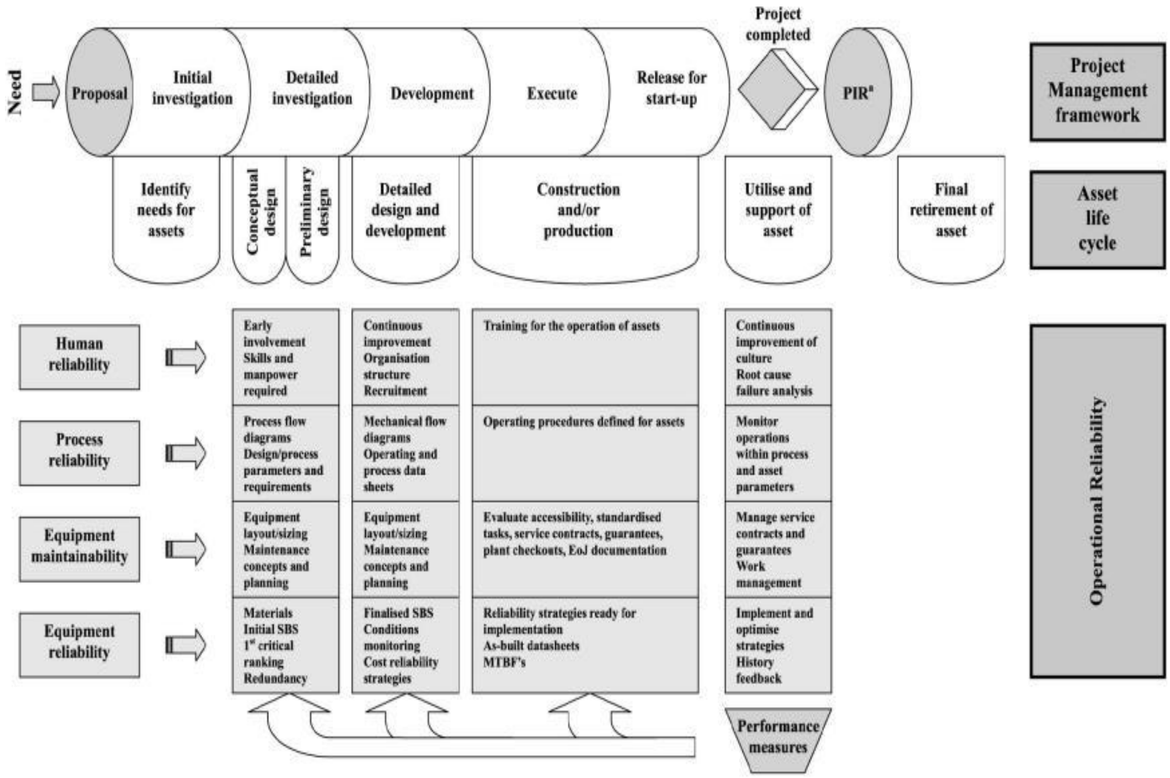
1. Need Identification

   This marks the first step towards the investment moves of an asset in the process industry. The identification of need focuses on investigating and evaluating the process requirements of the asset. Little is known at this stage of the project and the project description is more on broad terms like the number of barrels of crude oil that would be processed in a refinery, the number of megawatts of electricity that would be generated by a power plant.

2. Conceptual and Preliminary design

   This stage involves the generation of different concepts of the asset or project to be embarked on. This concept generation could be in form of brainstorming, Delphi method (where some panel of experts come together with their different ideas and views of the project) etc. This stage involves team of multi-skilled personnel from different discipline like operation, production and maintenance discipline who come together to ensure that human reliability is instilled in the investment project. This, they do by generating different concepts of the project to be executed and making initial assumptions regarding human capacity and skills required in the operation & maintenance (O&M) of the facility and developing process flow diagrams (PFD) which illustrate the basic flows that are expected in the system to be produced. These PFDs, developed at this stage are the first input towards system process reliability and they show key features and deliveries of the stage, the main equipment and the design parameters (pressure, temperature, flow), mass balance and control etc.

Issues concerning maintainability of asset or equipment are addressed in the preliminary stage by equipment layout study. Such study gives a rough assumption of the complexity of the processing plants, number of equipment to be used in the plant, size of the facility etc. The reliability issues at this stage shifts from human to equipment reliability and as such, reliability questions regarding the equipment are answered at this stage. One of such questions which is the anticipated design life of the facility is important at this stage as it forms a major reliability input to a lot of issues. Figure 4, represents the relationship between the lifecycle and the reliability of an asset.
Material selection is also done at this stage and involves professionals mainly engineers from design, metallurgical, maintenance and reliability discipline. Among the various needs of the process flow diagram is the derivation of high level system breakdown structure (SBS).



Note: [a]PIR refers to the Post Implementation Review

Figure 4: Asset life cycle management (ALCM) model (Schumen and Brent, 2005)

This, when derived from the PFDs is used to visualize the functional position of a piece of equipment according to the process in which it operates. This gives rise to equipment ranking according to their criticality, as such enabling for better understanding of the equipment and also assisting in identifying equipment or systems that are critical for normal operation. This also helps in decision making as it regards redundancy. Knowing the expected output, gives a clear idea of the impact that an equipment may have on the system process and with this, decisions are made on the systems that must have other systems standby in case of any eventuality, so as not to hamper the progress of the entire system. The computerized maintenance management systems (CMMS) offers a good platform for entering the results in schedule and task lists of the reliability strategy. The CMMS at this stage is not fully populated.

3. Detail design and development

   At this stage, there is detail presentation of the system process development. During the stage, the PFDs are developed into mechanical flow diagrams (MFDs). MFDs illustrate all equipment and interconnecting piping, materials, design and operating data location of instruments and pressure relieving devices (Schuman and Brent, 2015). MFDs and process data sheets provide information about sizes, materials and layouts that provide the scope for the first-round requirements for equipment maintainability. Some maintainability requirements like minimum distances between equipment can be specified at this stage by the vendors and contractors even though there is not yet a 3-dimensional view of the equipment.

   This stage also calls for more active participation of O&M personnel since more detail about the process and equipment becomes more available. The man power assumptions that were made earlier are further refined into an operation organizational structure (OOS), thereby giving rise to the various departments of the organization. Recruitment of suitable personnel could begin depending on the duration of this and the following stage.

   Since some equipment were not included in the former stage, criticality ranking is revisited now that all the equipment is included. The equipment that have been marked critical are subjected to failure mode effect analysis (FMEA) to identify the possible failure modes. This helps in the development of appropriate maintenance strategy for the equipment. Such strategy could be preventive or predictive in nature in that case the strategy either tries to prevent the failure or predict the possible cause and the time the failure would occur. Such, could be in terms of monitoring the equipment condition and being able to predict its condition with the help of some equipment monitoring systems. A situation where there is no preventive or predictive strategy for such equipment, the equipment can be run until it fails. In such case, depending on the criticality of the equipment, a standby equipment could be switched over to, to replace the failed one until it has been restored back to order.

For the safe operation of equipment and for cost-effectiveness, it is not advisable to operate equipment within their expected reliability parameters. Analyzing the trade-offs between O&M costs and the initial capital expenditure, gives one an idea of what to trade-off to select the best solution.

Having done the criticality ranking and having defined the reliability strategy, improved decision can now be made concerning on-line monitoring systems, comparing the installation costs of such system with the maintenance expenditure and the potential production loss due to equipment failure gives a good cost-risk study of the system.

4. Construction and Production

This is the execution stage of the system and it involves the actual construction / production of the system or process facility within the project management framework. The operation and maintenance personnel are fully involved towards the completion of the project before the start up or the commissioning stage of the project. For the operating personnel, the pre-commissioning and commissioning periods are very important periods during which valuable training opportunities concerning the project are fully exploited.

The actual accessibility evaluation is performed at completion, although it is late to make major changes to the project at this point. Yet it is advisable to consider recommendations made at this point.

Spare parts requirements are evaluated at the same time the equipment is procured and constructed. Conducting cost-risk studies at this point helps in decisions concerning the number of expensive, slow moving spares that should be kept or not. All spare parts should be kept ready before the commissioning just in case there is a failure to prevent unnecessary downtime. Much emphasis is laid on the future maintenance of the equipment by identifying the special tasks required for such maintenance and the tools are procured or constructed during the construction phase to ensure that the equipment receives appropriate maintenance after commissioning. All the necessary maintenance trainings are completed at this stage to ensure human reliability.

Tender evaluation of technical conformance to specifications and capital layouts are done at this stage. The maintenance of the equipment in some cases are contracted out to a supplier. Such agreements make it more economical for the supplier to supply equipment with the lowest life-cycle cost (LCC). This will also be of benefit to the client since more reliable equipment with fewer breakdowns and less production losses will be supplied by the vendor.

The O&M personnel get involved with plant checkouts towards the end of the construction and this involves the confirmation and approval of conformance to process and maintainability requirements. Such checkouts are better done with skillful and experienced people since it is very necessary for process reliability.
During the commissioning of the equipment, end-of-job documentation like operating manual, code data books and as-built drawings are made available. It is expected that at the end of this stage, all equipment should have a suitable reliability and the CMMS fully populated to implement such strategy after commissioning.

5. System utilization and life cycle support

The focus at this stage would be to operate the plant or equipment within the design limits to ensure process reliability during its lifecycle. The parameters required for the system reliability were defined and developed during the previous stages and operating the equipment outside the design parameters could have adverse effect on the equipment condition and so in other to ensure equipment reliability and process integrity care should be taken at this stage not to operate the equipment beyond the design parameters. From the production perspective, it is important to operate the asset at the most effective and efficient throughput while from maintenance perspective, operating the equipment outside the design parameters could have adverse effect on the equipment, so there tends to always be a clash of purpose between production and maintenance during this stage.

In such situation, an effective management system is required to monitor the operations and flag off deviations from the normal operations. Efficient work management process is executed at this stage through the implementation of those reliability strategies that were developed and entered in the CMMS during the previous stages. It is the duty of the asset operator at this stage to gather the data on the plant and feed them into the CMMS thereby building the foundation for the analysis of reliability. Such data is used to test the effectiveness of the reliability strategy and in situations whereby such strategy is not as effective as expected, the data is usually revised for better effectiveness. Such data are also used for conducting root cause analysis to eliminate defects.

Work management is important since it reduces the mean time to repair (MTTR) which is the main measurement for equipment maintainability. To ensure that work is identified in time, to make descriptions clear enough for the maintenance planner and supervisor, effective management process and system should be followed. Such system ensures that tasks that are regarded as high priority tasks are given the necessary attention within the time limit. This invariably allows for better planning and scheduling of less urgent or less important tasks thereby reducing wastages and ensuring that both services and materials are always available when the job starts. At this stage, online condition monitoring and scheduled condition based maintenance tasks are carefully executed, monitored and corrective actions taken when there are deviations.

6. Retirement

In actual sense, the design of assets is usually for a finite time but in most cases like in plant design, they out-stay their design-life. In their useful life, some parts may get worn-out and could require some replacement. The replacement is usually done but it’s rare that the whole asset (especially when it’s a plant) will retire at a time. The system is designed with the mindset that there is a retirement stage and so such design is done in a way that the retirement and disposal of the asset is carried out at a minimum cost and in the most environmentally friendly manner. In cases where the retired system needs replacement, the complete asset management framework is judiciously followed with the corresponding system development steps.

The measurement of the overall effectiveness of equipment (OEE) entails its availability which relates to its reliability. The reliability of an asset is the probability that a component or an entire system will perform its function for a specified period, when operating in its design environment (Carlo, 2013). This depends on the environmental conditions, usage or operation of the system.

In the presented framework of figure 4, the operational reliability which is the flexible process that optimizes people (Schumen and Brent, 2005) allows organizations to be successful while minimizing cost (OPAH, 2015). This has its focus on four major areas, namely:

- Human reliability: At the early stage of project conception and preliminary design, human reliability is ensured by involving multi-skilled personnel from various disciplines like operation, production and maintenance. To further ensure human reliability, initial assumptions are made regarding human capacity and the required skills for the operating and maintenance of the asset or facility. This could be in the form of organizing training programs for a new technology. To further enhance human reliability, the O&M personnel are trained during the construction stage and care is taken to complete the training before critical startup to ensure that they are ready for the system. Some other training opportunities arise during the pre-commissioning and commissioning periods which serves to ensure that human errors are totally reduced to minimum. Human errors which are, a set of human actions or activities that exceeds some acceptable limit (Swain, 1989) are demonstrated by large-scale accidents that occur in both low- and high- risk industries. These errors arise due to human interactions with the system. Such interactions like in the design and production of the system, between operators and repairers of the system can be reduced through human reliability assessment. Human reliability assessment aims at assessing the risks attributable to human errors or factors and reducing system vulnerability to human error impact (Kirwan, 1994).
  This is achieved by its three main principles of (1) human error identification which answers the question “what error can occur?” (2) human error quantification which answers the question “how likely are they to occur?” (3) human error reduction which aims at minimizing its error likelihood.

Through the early lifecycle stages of a system, error assessment consists of early involvement of skills and man power required while the later stages involve continuous improvement of culture, root cause identification and failure analysis.

- Process reliability: This covers the various methods for identifying problems which have significant cost reduction opportunities for improvement. Such problem identification is done at the early stage of the system development with the use of process flow diagram (PFD). PFDs illustrate the basic flow of the process while showing the main equipment and their design parameters like pressure, temperature etc. Further down the stage, these PFDs are developed into mechanical flow diagrams (MFD) which graphically illustrate all equipment and interconnected piping, materials, design and operating data, location of instruments and pressure relieving devices.

- Equipment maintainability: This is the measure of the ability of a system or component to be retained in or restored to a specific condition when maintenance is performed by personnel having specified skill levels using prescribed procedures and resources at each prescribed maintenance and repair. Maintainability aims at designing the system in the most reliable and maintainable way to minimize the cost to support a system and maximize the availability of the system. At the early stages of the equipment, it involves equipment layout, sizing and planning while the later stages focus on service and contract management, work force management etc.

- Equipment reliability: In this, the anticipated design life of an equipment/facility is determined. This serves as the input to all reliability issues and LCC analysis. With the contributions from different disciplines, ranging from design engineers, metallurgical engineers to reliability engineers, material selection is done. System breakdown structure is derived from process flow diagrams (PFD) to visualize the functional positions of equipment according to the process in which it operates while criticality ranking process which enables for better understanding of the equipment is done based on the process function of the system.

3.3 Asset Integrity Management

The concept of integrity, has been arbitrarily defined and mostly associated with humans and organizations with different views from different people (Becker, 1998). Integrity on its own has different meanings when used in different settings. In an organizational setting, integrity could mean trust in a person (Hosmer, 1995; Butler and Cantrell, 1984). In manufacturing industries, integrity could mean the assurance that machines will not breakdown or produce below an expected standard for a certain period while in process industry like the oil and gas (O&G), integrity could mean the assurance that flowlines used to transport O&G well streams from the well head to the production manifold has no leaks and that the hydrocarbons are well contained inside the flowlines (Ratnayake, 2010; 2011).

Asset integrity has been defined as the ability of an asset to perform its required function effectively and efficiently whilst safeguarding life and the environment (Ratnayake, 2012). Assets used in industries usually undergo a gradual decline in integrity (as presented in figure 5) during their operation and it has been established that with maintenance and modification, asset integrity level can be upgraded, the main challenge

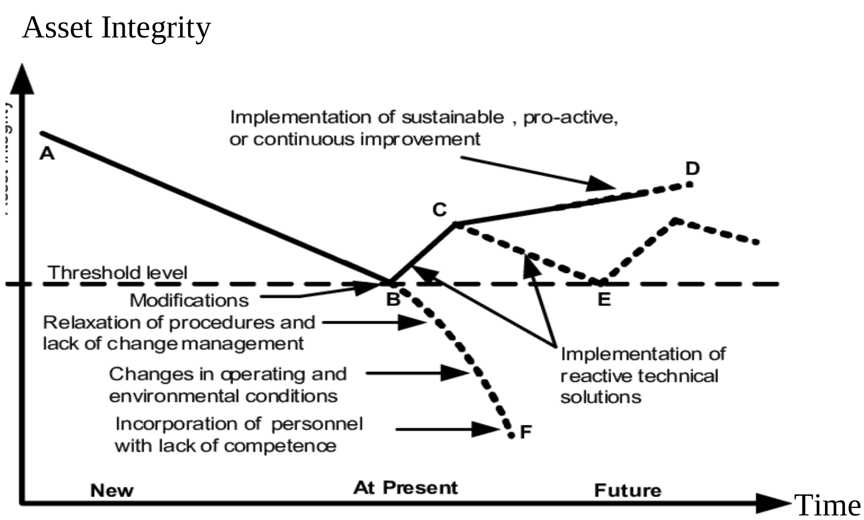


Figure 5: Asset integrity scenario over the operational life of an industrial asset (Ratnayake , 2012)

remains in the sustenance and continual improvement of such integrity level throughout an asset life cycle so as not to fall below the threshold level as specified by the regulatory authority (Ratnayake, 2012). For such could undermine a company's competitive advantage and could lead to catastrophic consequences.

In the process industry, asset integrity is a complex issue with many facets and the goal, is to establish such integrity throughout the entire life-cycle of an asset i.e. through the design, manufacturing, operation, inspection, maintenance to the decommissioning stage. Figure 6, represents the elements that have impact on the integrity of an asset.

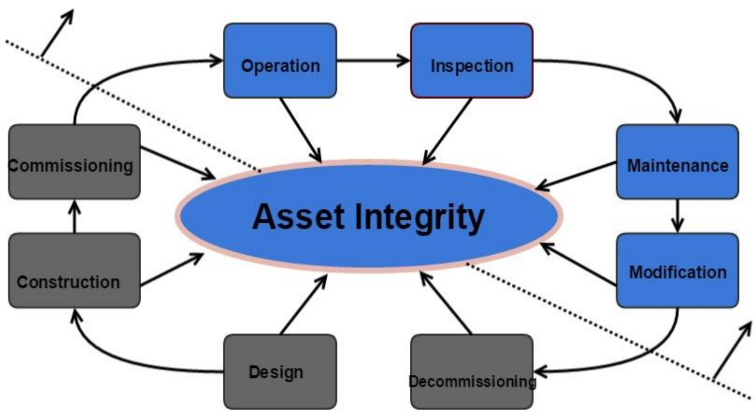


Figure 6: Elements that have impact on the integrity of an asset over its entire life-cycle. Source: HSE (2006) but adopted from (Hassan and Khan, 2011).

The activities in the upper part of the dotted line are grouped into operational integrity (which involves all operation related activities) and mechanical integrity (which is the assurance that

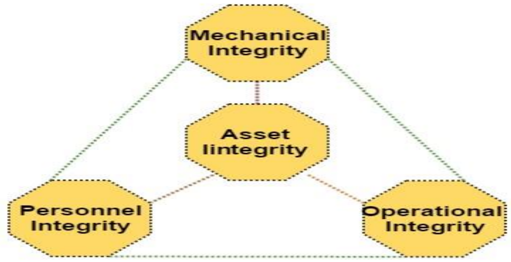


Figure 7: Relationship between asset integrity with its major contributory elements (Hassan and Khan 2011)

there are appropriate work processes for inspection, maintenance system and data management to keep the operations alive). Inspection, maintenance and modification fall under the category of mechanical integrity while the operators, maintenance personnel, employees, inspectors, contractors, engineers and other personnel that are involved in designing, specifying, installing as well as decision making are all categorized under personnel integrity (Hassan and Khan, 2011) which is the assurance that there is appropriate experience, knowledge, computer manning and decision making to operate the asset as intended throughout its entire life-cycle. Ratnayake and Markeset (2011); OGP (2008), developed measures to be taken to ensure the integrity of an asset for every stage in its life-cycle and went further to stress the need for adequate monitoring and reviewing of the performance of such integrity by developing some key performance indicators (KPI) used for such performance monitor. De Jong, Marx and Vos (2009) ; Ratnayake and Markeset, (2012) stated that the overall asset integrity includes (1) operational integrity (2) mechanical integrity (3) personnel integrity. Figure 7, represents the relationship between asset integrity and these major contributory elements. Therefore, the management of these three categories of asset integrity (AI) is needed to ensure the overall asset integrity which will invariably lead to safe process and optimized usage of the asset.

Asset integrity management (AIM) is the means of ensuring that the people, systems, processes and resources which deliver the integrity are in place, in use and fit for purpose over the life-cycle of the asset (Ratnayake and Markeset, 2012).

3.3.1 Asset Integrity Performance Indicators

Since it has been established that asset integrity is a major concern in high risk and capital intensive business like the oil and gas (O&G) industry (Kishawy and Gabbar, 2010; Hassan and Husein, 2013; Hussein and Khan, 2011), the management of the integrity of assets which ensures that people, processes and plant resources which deliver the integrity are in place and fit for purpose over the whole lifecycle of the asset (Hassan and Husein, 2013) has to include a means for monitoring the performance of the integrity so as not to fall below the threshold level. Such monitor according (OGP, 2008) should be fact-based not judgement-based and includes; incident and accident investigations, audit findings, benchmarking and lesson learned from external events, barrier performance standard verification and key performance indicators.

For this research, Performance Indicators are used to checkmate the level of integrity of oil and gas (O&G) pipelines so as not to fall below the given threshold.

Asset integrity indicators otherwise known as performance indicators which are quantitative or qualitative factors or variables that provide simple and reliable means to measure the achievement, to reflect changes connected to an intervention or to help assess the performance of a development actor (Schwab, 2010) should also be able to provide feedback on what is happening for the user to be able to figure out the appropriate actions to respond to changing circumstances (KP3 report, 2007). The inherent risks that accompany oil and gas pipeline failures are so enormous that the means of monitoring the integrity should be aimed at reducing the risks that exists in all aspects of the oil and gas pipeline maintenance and operation. Such risk reduction could be through the reduction of the chance (probability) of occurrence and reducing the consequences as well. This means that the monitor of the performance of asset integrity should be based on the risk-based system that covers both the active and reactive aspects.

The risk-based indicator system is a risk information tool that can generally be used to monitor asset performance and to alert the user if asset performance exceeds certain level or follows any undesired trend (Hassan and Husein, 2013). Figure 8 illustrates indicator pyramidal hierarchy for monitoring the integrity level of assets.

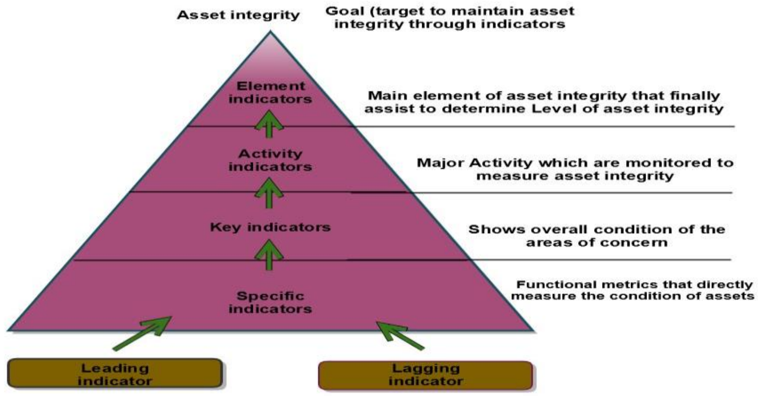


Figure 8: Hierarchical indicator pyramid for monitoring the integrity level of assets (Hassan and Khan, 2011)

This allows problems to be identified and corrective actions taken to avert the occurrence of serious incidents. Various risk -based indicator systems have been suggested by researchers among which are leading and lagging indicators (Hassan and Khan, 2011), direct and indirect indicators (Martorell et al, 1999), qualitative and quantitative (Gordon, 2008; Kotula et al, 2014; Mohanty and Gahan, 2013).

This research adopts the leading and lagging indicator system for the monitor of the integrity level of oil and gas pipelines at the different leverage points under study. The performance indicators which measure or record actual integrity failures are called lagging indicators (OGP, 2008) and is simply the output measure of the lead indicator (Ahren and Kumar, 2004) while the indicators that assess the health of the safeguards controls which make up the barriers are the leading indicators (OGP, 2008) and are also known as the performance drivers (Liyanage et al, 2007). While the leading indicators predict or drive the bottom-line performance results, the lagging indicators show the outcome of operational performance (Parmenter, 2007).

3.3.2 Integrity management of oil and gas (O&G) pipelines

The integrity of O&G pipelines simply brings the concepts of failure prevention, inspection and repair into focus, not excluding the products, practices and services that help operators maximize their assets. Due to the high capital intensive nature of O&G pipelines and the threat, the degradation of pipelines could cause to life and natural environment, its integrity design, monitoring and management have become very vital (Kishawy and Gabbar, 2010). Such integrity begins at the project conception stage and should run through to the decommissioning stage. Figure 9, is an illustration of IDEFO pipeline integrity management model that runs through the entire life cycle of the pipe

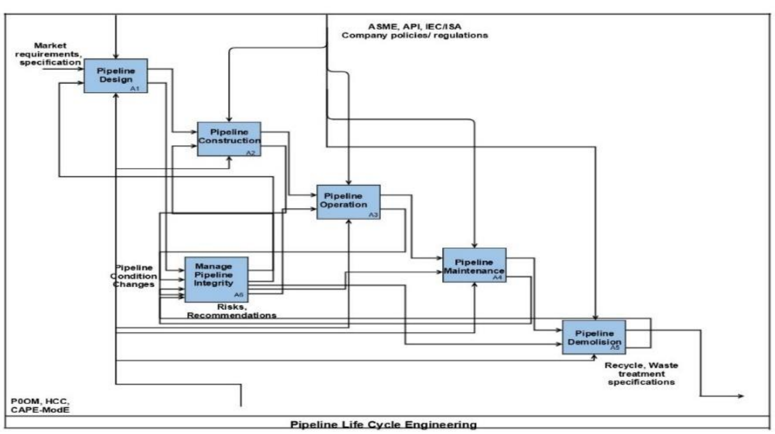


Figure 9: IDEFO based activity model for pipeline integrity management (Kishawy and Gabbar, 2010)

For an effective O&G pipeline integrity management, a pipeline integrity management program (PIMP) is designed by pipeline operators as mandated by the state to identify the most serious risks unique to the company's pipeline to set priorities in risk reduction, so that man-power and financial resources can be effectively used to minimize risks and maximize safety (Liu, 2003). Such program according to Liu, shall contain the following components: (1) a process for identifying pipeline segments that could affect a high consequence area (2) a baseline assessment plan (3) an analysis that integrates all available information about the integrity of the entire pipeline and the consequences of failure (4) criteria for repair actions to address integrity issues raised by the assessment plan and information analysis (5) a continual process of assessment and evaluation to maintain pipeline integrity (6) identification of preventive and mitigation measures for protecting the high consequence area (7) methods to measure the program's effectiveness (8) a process for the review of integrity assessment results and for information analysis.

3.3.3 Pipeline Integrity Threats

To gain real insights on the integrity of pipelines, one needs to identify the different threats or risks that an operating pipeline faces over its entire life-cycle since these threats weaken the pipelines and significantly shorten their life span (Pica corp, 2016)
According to ingaa.org (2013) nine of such threats have been identified in the ASME B31.8S standard and they fall under three separate categories:

- Time-dependent threats: These are threats that grow over time and include internal corrosion, external corrosion, creep and cracking mechanism
- Resident threats: These are threats that do not grow over time, they rather tend to act when influenced by another condition or failure mechanism. These include: mechanical damage from construction/fabrication, material and construction defects like defective longitudinal pipe seam, pipe body and joint welds, maintenance, third party excavation/sabotage etc.
- Time-independent threats: These are threats that are not influenced by time. They include: human error, incorrect operation, device failures and malfunction, excavation damage, earth movements such as earthquakes, landslips or telluric currents, outside forces or weather related threats such as high winds, rough seas or cold/ hot temperatures etc.

Table 3: Ranking of causes of oil pipeline incidents that inhibits productivity in Nigeria using mean rating score (X) (Adebayo and Dada, 2008)

Sn	Cause of oil pipeline incident	Mean rating score(X)	Ranking
1.	Sabotage (vandalization)	5.00	1st
2.	Mechanical impact (third party damage)	1.35	4th
3.	Material defect	1.11	8th
4.	Equipment failure	1.33	5th
5.	Operator errors	1.05	10th
6.	Geotechnical forces/ hydrodynamic	1.11	10th
7.	External Corrosion	1.88	2nd
8.	Internal corrosion and hydrogen induced cracking	1.38	3rd
9.	Over-pressurization	1.12	7th
10.	Internal expansion force	1.00	11th
11.	Fatigue	1.00	11th
12.	Weld crack	1.16	6th
13.	Improper repair weld	1.00	11th

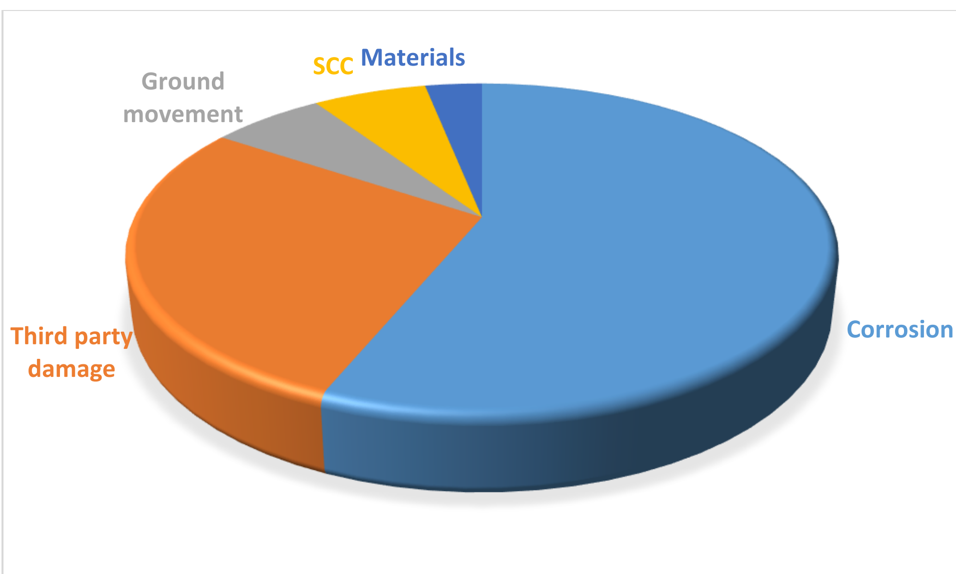


Figure 10: Percentage distribution of oil pipeline incidents in Nigeria (Adebayo and Dada, 2008)

According to Adebayo and Dada (2008) as presented in table 3 and figure 10. Sabotage (Vandalization) was discovered to be the most predominant threat facing pipelines in Nigeria.

- Sabotage (Vandalization): This refers to the illegal or unauthorized activities that involves the destruction of oil pipelines to disrupt supply or the puncturing of oil pipelines to siphon crude oil or its refined products to appropriate it for personal use or for sale in the black market or any other outlet (Onuoha, 2007). Such acts include bunkering, breaking oil pipelines to siphon fuel, fuel scooping from burst oil pipelines and the deliberate act of oil terrorism. This was traced to the long history of neglect, marginalization and repression of the host communities whose counter effect has been lack of development and widespread poverty and discontent among people (Adebayo and Dada, 2008).

- Corrosion (external and internal): These ranked second and third respectively. Corrosion causes could range from the exposure of pipelines to external influences (like the atmosphere, micro-organisms etc. at high relative humidity resulting in the formation of water that contains dissolved salts) to contact between dissimilar metals that are not controlled properly. Corrosion was identified as the major cause of pipeline failure in the US and Europe and has resulted in 75% of structural problems in pipeline while pipeline vandalization(sabotage) remains the major systemic risk facing pipelines in developing nations especially Nigeria and closely followed by corrosion (Adebayo and Dada, 2008).

- Mechanical impact: This occurs in the form of dents and gouches, reducing both the static and cyclic strength of offshore and onshore pipelines. It ranked fourth in the list. Corrosion and mechanical impact were identified as the major threats to onshore and offshore pipelines in Western Europe and North America (Macdonald et al, 2006; Cosham, Hopkins and Macdonald, 2007). The failure in the operational status of equipment such as compressors, pumping stations or emergency -shut-down valves could lead to a major blowout in pipelines.

These threats occur at the different stages of pipeline life cycle therefore their identification by pipeline operators mark the basis for pipeline integrity and programs are designed for this. There may be some circumstances where two or more of such threats occur coincidentally and independent of each other. Such coincident threat results in a greater likelihood of failure than when it is an individual threat.

To be able to tackle these threats, taking aggressive actions rather than defensive actions are recommended.

Such actions lie in ensuring the reliability of the pipeline which begins with the quality of line used (Kishawy and Gabbar, 2010). To keep up with regulations, economies and application, companies constructing new pipelines now have array of materials and coatings at their disposal that were not available a few years back. The ability to fine-tune alloys to meet the most demanding harsh conditions like high-temperature and pressure have been provided with advances in metallurgy.

Figure 11, presents the recent causes of pipeline failure in Europe as recorded by five different databases accros Europe namely: EGIG, UKOPA,DOT, NEB, APIA,Gosdortehnadzor from 1963-2005.

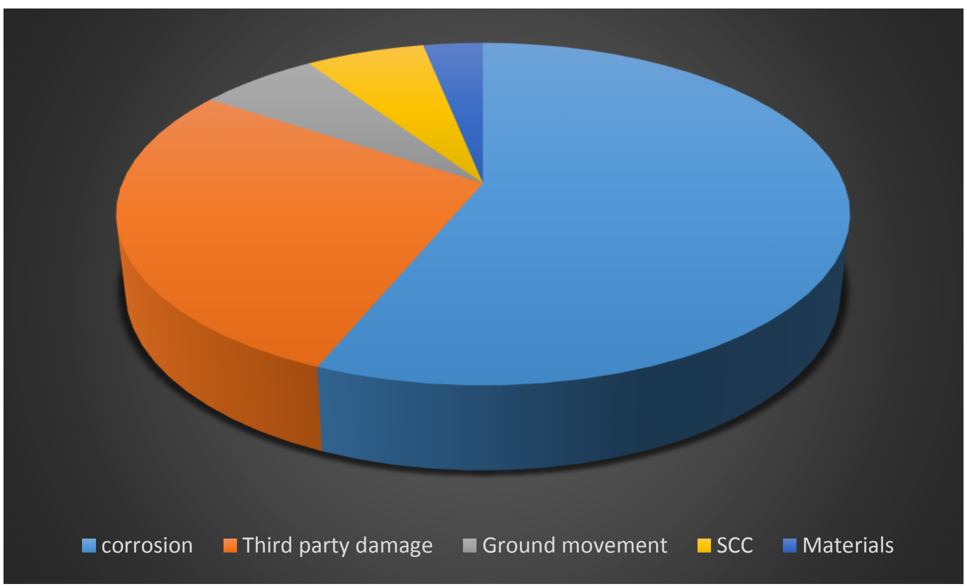


Figure 11: Causes of gas pipeline ruptures in Europe (Bolt, 2006)

Corrosion remains the highest cause of gas leakage, mainly occurring in thin-walled pipelines (less than 10mm). From the observation recorded in the data, no corrosion was observed on pipelines with wall thickness of more than 15mm and of all the corrosion 77% were external, 19% were internal and 4% were unknown (Bolt, 1999).

3.4 The Leverage Points

This section presents the study into four selected leverage points in a bid to properly manage the problem of sabotage and vandalization that is commonly experienced in developing nations.
A leverage point is a point in a complex system (a corporation, an economy, a living body an ecosystem) where a small shift in a subsystem results to a significant change in the entire system (Meadows, 1997).
Having established that corrosion remains the major pipeline integrity threat across US and Europe, while pipeline sabotage and vandalization remains the major threat in developing nations like Nigeria, corrosion is a threat within the system boundary, therefore the solution should be within the system boundary. Sabotage on the other hand is a threat from external source, as such the proper management of sabotage should extend beyond the system boundary and consider some factors that are external to the system. In this case the stakeholders.

Therefore, to be able to properly manage these two threats especially pipeline sabotage, four leverage points are selected where necessary changes are to be effected. The selected leverage points are:

1. The design stage (Leverage point 1)
2. The Operation and maintenance stage (Leverage point 2)
3. Pipeline monitoring and Inspection (Leverage point 3)
4. The mindset or paradigm out of which the pipeline (Leverage point 4)

Figure 12 is the schematic diagram showing the different leverage points for systemic change currently under study in an oil and gas system

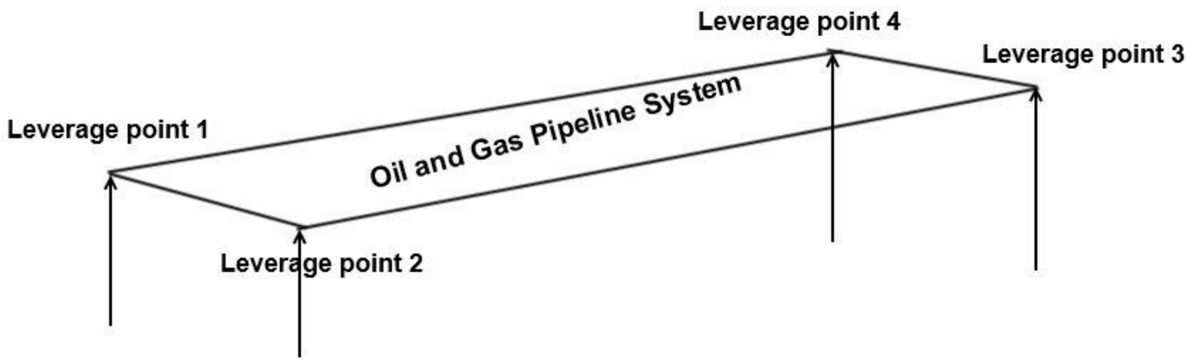


Figure 12: Schematic diagram of the different leverage points in an oil and gas pipeline system

3.4.1 The Design Stage (First Leverage Point)

The integrity design of pipelines is governed by various standards, codes and regulations applicable to a location but O&G pipeline design follow some general steps (Liu, 2003 pg. 354): (1) Load determination (2) Stress determination and /or deformation of the pipe, also known as critical performance (3) Performance comparism with performance criteria established by codes and standards (4) Final selection and construction method based on the design

The design of such pipes is based on pressure consideration which gives rise to three main categories: (1) High-pressure pipes in which the internal pressure of the pipe is so high that it dominates the design (2) Low-pressure pipes in which the internal pressure is usually low or negligible, therefore the design of the pipe is governed by external loads. (3) Intermediate-pressure pipes in which the internal pressure and external loads are of similar magnitude which makes both to be considered while designing the pipeline.

O&G pipelines stretch through long distances while transporting the products (petroleum and natural gas) and so are subjected to very high internal pressure often above 1000psig and sometimes above 3000psig. Therefore, the integrity design of such long stretching pipes does not only consider the amount of pressure to which the pipes are subjected to but also some other certain factors like temperature changes for pipelines with rigid support and pipe bending for pipes supported uniformly (Kishawy and Gabbar, 2010).

At this stage, the focus should be to establish how easy and efficient it would be to take care of integrity in operation. Proper evaluation of threats and failure modes are done at this stage by considering how these threats and failure modes can change through the lifetime of the pipeline. For instance, how the population along the pipeline route can change overtime, wave size and sea current, how third party activities like trawling, population, construction activity, shipping traffic can change over time (Lind, 2013). The robustness of the design with respect to variations in threats and failure is ensured at this stage in order that it does not require much attention during operation since a more marginal design may require more comprehensive follow up.

Attention should be paid to the associated cost that is related to potential production stop to enable some other work that could come up during the operation of the pipeline. For instance, should there be a future road or railway that could be built after the pipeline has started its operation. If this is not considered during the design stage, the pipeline may have to be shut down to enable heavy construction crossing over the pipeline thereby incurring unnecessary costs that are associated with equipment shutdown.

Also worth considering at this stage is route selection (Lind, 2013). Decision should be made as to whether to go through some rough terrain (for instance with wet marsh or steep slopes) to achieve a shorter route and lower investment cost or taking longer route through less difficult terrain (for instance more flat and accessible terrain). This decision is important for the future operation of the pipeline mostly when failure occurs in the pipeline because a rough terrain might be more difficult to access thereby requiring a longer repair time and higher production loss in situations where there is damage in such area. So, it is important to consider the risk for damage within this area and this should be done when evaluating the route. Such risk could be reduced by having a more robust design in this section. Testing and maintenance of valves is another important issue that should be considered at this stage and the pipeline should be designed in such a way that these could be carried out with no or minimum production stops.

Due to the high pressure that oil and gas pipelines are subjected to, they are designed with a material primarily made of steel. The choice of steel is basically for its high strength and ductility which allows the pipe to bend and can receive very large impact without fracture. The design of such steel pipe is in such a way as to be long, sometimes more than 1000mi with fewer booster pumps for oil pipeline or compressor stations for gas pipelines. Such design of fewer booster umps or compressor station along a pipeline is for economic reason as it reduces both construction and operating cost.

3.4.1.1 Corrosion of Oil and Gas Pipelines

Designing of O&G pipelines with steel comes with a major problem which lies in the fact that steel corrodes.

Corrosion, which is an electrochemical and time-dependent process (Cosham, Hopkins and Macdonald, 2007), is the degradation of materials due to its interactions with the environments (Shaw and Kelly, 2006; Peabody and Bianchetti, 1967). Pipelines that have been buried in the soil for more 5years of life, experience different types of corrosion and defects especially cracks which normally turn to defects. Such cracks are promoted to defects by a combination of stress (such as hoop or residual stress) and their natural soil environment which contain different amount of moisture and oxygen These cracks accelerate in thickness and continues, most especially during operation from primary size to critical sizes which normally result in sudden failure (Karami, 2012).

The different types of corrosion basically fall into two main categories:

(i) Pitting corrosion which is a corrosion whose length and width is less than or equal to three times the uncorroded wall thickness (ii) General corrosion which is corrosion with length and width greater than three times the uncorroded wall thickness. The various types of corrosion which include galvanic corrosion, AC corrosion, differential aeration and cracking, microbiologically induces corrosion etc. all fall under the two mentioned categories. Figure 13, represents the schematic illustration of the various types of corrosion that occur in pipelines.

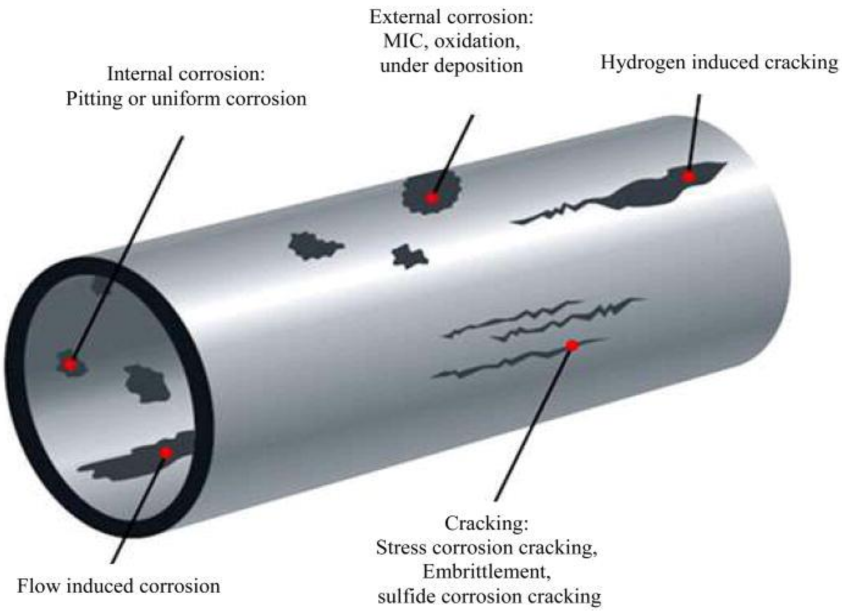


Figure 13: Types of corrosion in pipeline (Karami, 2012)

Corrosion has been identified as one of the major risks that undermines the integrity of pipelines and a summary of oil pipeline spill in the United states between (1968-1999) has structural problem (of which corrosion takes the lead) as 40% (Pipeline and Gas journal, 2003) while the economic impact of corrosion runs into $276 billion annually which accounts for 3% of US annual GDP (SPDC journal, 2006). In Europe corrosion, is identified as the major cause of pipeline failure (Bolt, 2006).

Noteworthy about corrosion is the gradual depletion of the metal (pipeline) which could occur at any part of the pipeline like the internal or external surface, in the base material, the seam weld, the girth weld and/ or the associated heat affected zone (HAZ) (Cosham, Hopkins and Macdonald, 2007).

The corrosion of pipelines at near ambient temperature which occurs in aqueous (water containing) environment is electrochemical in nature (Peaby and Bianchetti, 1967) and the aqueous environment is the electrolyte (moist soil in the case of underground corrosion). Corrosion generally involves two main processes:

(i) The removal of electrons (oxidation) of the metal also known as the anodic reaction.

$Fe \longrightarrow Fe^{++} + 2e'$--- (1)

(ii) The consumption of those electrons by some other reducing agents such as oxygen or water also known as the cathodic reaction.

$O_2 + 2H_2O + 4e' \longrightarrow 4OH$-------------------------------------(2)

$2H_2O + 2e' \longrightarrow H_2 + 2OH$----------------------------------(3)

Figure 14, represents the schematic representation of the electrochemical process involved in the corrosion of pipeline.

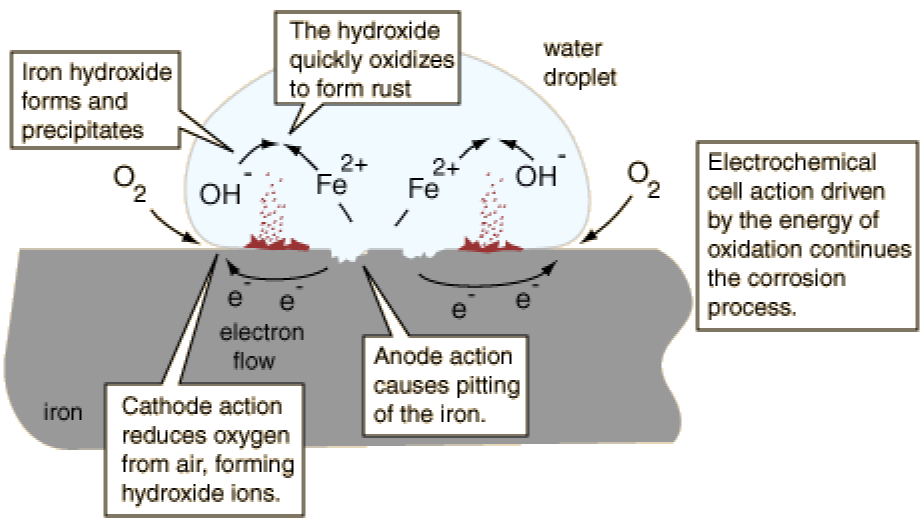


Figure 14: Schematic representation of the corrosion process of a pipeline (Chem 1.com)

To account for corrosion loss, O&G steel pipes are designed to withstand high internal pressure that is generated by the flow of the fluid through the pipes by allowing some extra thickness for protection against the loss of thickness due to corrosion (Liu, 2003). Such design also gives them adequate strength against external loads which is usually less than the internal loads of the steel pipes. Therefore, the main issue in the integrity design of steel pipes is the internal pressure and corrosion. For this reason, much attention is not paid to the levelling and grading of land before such pipes are laid which greatly reduces the construction costs of steel pipelines but in some cases, paddings are provided to protect the steel pipelines from possible coating damage that may result from laying pipe on hard rocks.

3.4.1.2 Oil and Gas Pipeline Corrosion control

Since both the cathodic and anodic reactions must take place for corrosion to occur, prevention of either of the process reduces corrosion. Therefore, all effort that is made towards prevention of corrosion in pipelines are geared towards mitigating/reducing one or both half-cell reactions. Such efforts are as follows:

1. Coating

   The reasoning behind coating is that if pipeline metals could be isolated from contact with the surrounding earth, no corrosion would occur. Pipelines when coated appropriately stop corroding, at least for their design life but the aim is always for the coating to last as long as the pipeline remains in service. Coating material would be completely effective as a means of corrosion control if the material:

   (i) Is an effective electrical insulator (ii) Can be applied with no breaks whatsoever and would remain so during the backfilling process (iii) Constitutes an initially perfect film that would remain so during the backfilling process (Peabody and Bianchetti, 1967). Based on the stated terms, the coating materials in use at present for high pressure pipelines are FBE (fusion bounded epoxy), coal tar and asphalt, enamel etc. Figure 15, represents a deteriorating coating on a 24-inch pipeline that was due to poor coating material which was used for the coating of the 24-inch pipeline.

Fig. 15: Deteriorated coating on a 24-inch pipeline (Wilke et, al 1997)

2. Cathodic Protection (CP)

   This technique involves the reduction of corrosion rate on a metal surface by making it the cathode of an electrochemical cell. This is based on the principle that anodic and cathodic areas exist in the surface of a pipeline and that current flows from the steel pipeline into the surrounding electrolyte (soil and water) at the anode leading to the corrosion of the metal and that at the cathodic area, current flows from the electrolyte on top of the pipe surface thereby reducing corrosion. Based on the above principle, corrosion rate is reduced if the exposed metal on the surface of the pipeline could be made to collect current. It is on this principle that cathodic protection is based. Figure 16, is a schematic diagram of a typical cathodic protection installation.

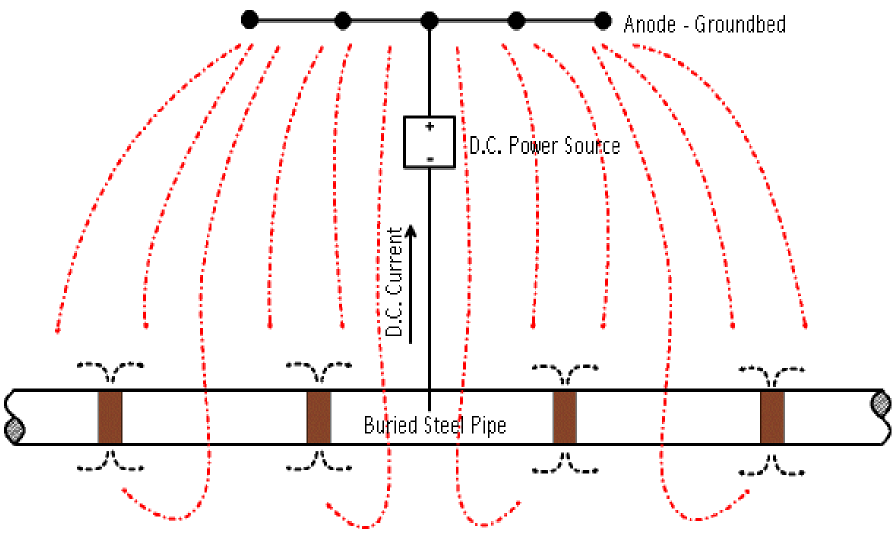


Figure 16: Basic cathodic protection installation

Cathodic Protection basically exist in two forms:

1. Sacrificial (or galvanic) system

   In this system, a very active metal (Zn or Mg) is connected to each section of the pipeline. This metal corrodes and by so doing, discharges current to the pipeline. It should be noted that in galvanic CP, CP does not eliminate the corrosion, rather it displaces it from the structure being protected to the galvanic anode. The current from galvanic anode is usually limited therefore CP by galvanic anodes is normally used where the required current for protection is small.

2. Cathodic Protection with impressed current

   This was introduced to make up for the weakness associated with galvanic anodes (i.e. limited current). In this, current from external power source is impressed on the pipeline by using a ground bed and a power source, the most common being the rectifier. Other sources of DC electric power could be used for impressed current in this CP system.

3.4.2 Pipeline Operation and Maintenance (The Second Leverage Point)

The Operation and maintenance integrity of a pipeline entails understanding the purpose of the pipeline, how the pipeline was designed and constructed, the codes and standards governing the operation of the pipeline, the operational history of the pipeline and the pipeline's status (Liu, 2003).

Such operation and maintenance integrity procedures are recorded in (ASME B31.8 code, 1995). This code sets forth the engineering requirements that are internationally recognized for the operation and maintenance of pipelines and its encompasses the essential operation and maintenance plans that are required from pipeline operating companies. As it regards operations, it gives a standard for pipeline operating personnel, their training and educational program requirements. While for maintenance, it gives the standard for pipeline operating companies to follow in the maintenance and surveillance of their pipelines.

The codes and standards are summarized below and when well taken care of during the operation and maintenance stage of the pipeline, will go a long way in ensuring the integrity of the Pipeline during this stage:

1. Easy access to all documentation and a proper handover from the project's operator/ owner (for new pipelines) or previous operator/ owner (for existing pipeline)
   This documentation gives the design premises and the purpose for which the pipeline was constructed, thereby establishing proper integrity management. Once the purpose of the pipeline is defined, strategy and operational details must be laid out in an operation and maintenance (O&M) manual. Such strategy is usually planned around a set of operational parameters like, the discharge through the pipe, mean velocity, temperature range of the transported fluid, minimum and maximum pressures at various locations along the pipe, pump speed and head, valve closing speed etc. The manual should be made in such a way as not to only describe the routine procedure but also should be made to describe what needs to be done in various emergency situations such as when leak is detected. It should be made available not only to the operational crew of the pipeline but also for flow charts and computer program design which are used for automatic control of the pipeline system under both routine and emergency.
   The operation of the system within the design premises and performing regular checks to ascertain that the pipeline is operated within the design premises forms part of the risk assessment of the pipeline and a key issue in its integrity management.

2. Access to skilled human resources

   The operation of pipeline requires a good knowledge of pipeline engineering and many other related fields such as corrosion control, automatic control, fluid mechanics, structural engineering, machine maintenance etc. These require engineers and technicians who are skilled in these disciplines and trained to work together to keep the pipeline system running and maintained in good condition. The manning of the pipeline system by unqualified personnel/operators often results in improper operation of the pipeline and damage to the system which leads to frequent unscheduled shutdown. To reduce the influence of human factor on pipeline operation, modern computers and automatic control systems are employed in running the pipeline system.

3. Good procedure and routine for maintenance

   The pipeline's maintenance needs must be carefully assessed, the schedule and maintenance procedure clearly spelt out in the maintenance manual. Such maintenance fall into two main categories:

(i) Routine maintenance: These are upkeep practices carried out on pipelines on a regular basis with an eye towards preventing large-scale damage to oil and gas pipelines. These include not only the maintenance of the pipeline itself but also all the equipment needed for the pipeline to function properly like the pumps, motors, valves, transducers, flowmeters etc. Servicing and adjusting them according to their individual maintenance schedule, repairing and putting back to service as soon as possible any equipment that malfunctioned and replacing damaged and worn-out parts. On the part of the pipeline itself, the maintenance should also be carried out. Such maintenance includes: periodic checking of the cathodic protection system (for steel pipes), pressure testing all pipes for possible leak detection due to aging or corrosion and performing in-line maintenance or pigging to clear out debris (using cleaning pigs) and detecting possible damage (using inspection pigs).

(ii) Renovation (rehabilitation): This includes more reactive and costly measures that are taken when the exterior of a pipe is seriously corroded by the soil surrounding it or the interior of the pipe is seriously damaged by internal corrosion or incrustation. The notion of trenchless technology which is basically used for corroded steel pipes and cast iron used in conveying water through seriously damaged pipes is now finding its application in the oil and gas pipelines. Figure 17, is a schematic representation of a pipe section that has been treated with the trenchless technology.

This technology involves the installation of an in-situ lining or a smaller pipe inside the old pipe. Such technologies are gaining grounds in recent years in the O&G industry and are called trenchless because they do not require the digging of new trenches for new pipe laying (which usually proves to be very costly when it comes to densely populated areas in the city where it is difficult and costly to build new lines) making them to be considered as being environmentally friendly.

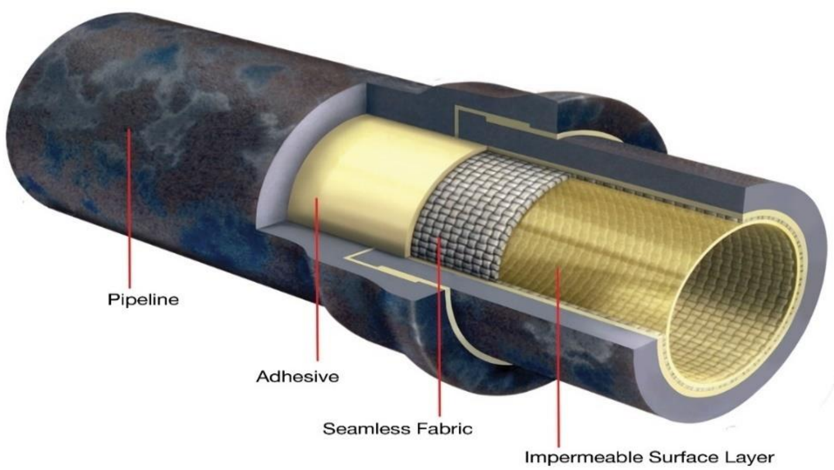


Figure 17: Schematic representation of a pipe section treated with trenchless technology (bing.com trenchless technology)

Through such renovation, the lifespan of a pipeline could be extended for another 30years or longer. (Iseley and Najafi, 1995) explored the different aspects of trenchless technology and with the current research going on, on trenchless technology, many pipes that have been seriously corroded in US and Europe now have the hope of being renovated and given second life. These trenchless technologies include:

(i) Cured-in-place lining: This involves using a flexible fabric tube that is foldable (deflectable) and inserting it into an old leaking pipe thereby forming a lining. Inverting the flexible tube under fluid pressure or pulling it into the pipe with a winch, allows the tube to advance deep into the buried pipe. Pumping fluid pressure into the tube causes it to inflate, thereby attaching itself firmly to the pipe wall. Figure 18, is a representation of a deteriorated pipeline being treated with the cure-in-place lining technology.

Figure 18: Deteriorated pipe being treated with cured-in-place lining (bing.com. cured-in-place lining)

The tube which originally is made of a thermosetting catalyst is filled with heated fluid like hot water or steam, the heat causes the resin to set, forming strong lining with the old pipe wall thereby protecting the old leaky pipe. Care must be taken to thoroughly clean the pipe interior before the insertion of the flexible tube into the pipe. Epoxy, polyester and vinylester are the common types of thermosetting resins used for such linings. Polyester which is the commonest has higher acid resistance than epoxy. Epoxy is adhesive is adhesive to pipe and preferred when the fluid in question has high PH values. Vinylester has superior corrosion resistance at higher temperature. It should be noted that the use of flexible tube slightly reduces the initial diameter of the corroded pipe.

(ii) Slip-lining: This involves inserting a flexible new pipe into an old pipe to rehabilitate the old pipe. The flexible pipe is usually significantly smaller than the old pipe to avoid difficulties that might be encountered at pipe-bends during sliding. This method results in significant reduction of pipeline diameter and thus a great reduction in the fluid that flows through the pipeline.

(iii) Pipe-bursting: This involves replacing old underground pipes with new ones of the same or slightly larger diameter without having to dig out the old pipeline. This is achieved through the in-situ bursting of the old pipeline and installing the new one using either the method of inserting mole into the old pipe or the method of using micro-tunnel machine which can burst old pipes. The old pipe is removed and the new one installed after the micro tunnel is formed.

(iv) Pipe-shrinking: This involves the compression and the deformation of a flexible plastic pipe such as high-density polyethylene (HDPE) or polyvinyl chloride (PVC) into a U-shaped cross-section resulting in a much smaller cross-sectional area than that of the original round pipe. The deformed and shrunk pipe having been pulled into the leaky pipe of larger diameter is inflated into its original shape and size using heat and internal pressure. After the liner is in place, the inward pressure is removed and the pipe gradually relaxes and expands thereby going back to its original size and shape, forming a tight fit between the liner and the old pipe.

(v) Patching and sealing: This is used for the repair of local damage to a pipe caused by accident or impact during construction. It involves patching (bandaging) the hole, cut or puncture from the external surface of the pipeline. Repairing a hole from the inside involves injecting resins through the whole otherwise known as chemical grouting. This method involves placing a forming bladder inside the pipeline at the location of the hole that needs to be sealed. The resin is then injected between the inflated bladder and the pipe until the outside surface of the pipe and the surrounding soil are saturated with the resin. The resin is then injected between the inflated bladder and the pipe until the outside surface of the pipeline and the surrounding soil are saturated with the resin, the resin is then allowed to set resulting in the sealing of the hole and the bladder is finally removed.

3.4.3 Pipeline Monitoring and Inspection (The Third Leverage Point)

This includes the various measures taken to ensure that the integrity of pipelines does not fall below the required level whose main objective is to monitor the pipeline condition and its immediate environment to determine or head-off damage to the pipeline thereby minimizing potential accidents and service interruptions due to pipeline neglect and safeguard company and public interest (Liu, 2003). Such measures include:

- Leak detection

Various methods exist for the monitor of leaks in pipelines ranging from the use of trained dogs to the more advanced method of satellite based hyperspectral imaging (Sivathanu, 2003; Scot and Barrufet, 2003). Leak detection technology has been classified as shown in figure 19. They are broadly classified into:

(i) Biological method: This is a traditional leak detection method where experienced personnel or trained dogs walk along the pipeline looking for patterns near the pipeline like odour emanating from the pipeline, listening to noises that could be generated by escaping products from pipeline hole. The effectiveness of this method depends solely on the experience of the trained personnel that is engaged in this monitor.

(ii) Hardware-based methods: These utilize hardware tools for the detection and localization of leaks in pipeline. These likes are visually observed or displayed on a screen. Such hardware tools include: sensors, infrared thermography, negative pressure detectors, gas detectors etc. These techniques have good leak sensitivity and are very precise in leak location but they are usually very complex to install which makes them very expensive. They are used where there is high pipeline risk potential like near the river, nature protection or in the transportation of hazardous waste (Golmohamadi, 2015). They include: acoustic sensor method, vapor sampling method, optical method etc.

(iii)Software-based methods which utilize computer software packages to detect leaks in pipelines. Such method includes: Mass or volume analysis, pressure point analysis, dynamic model etc.

Zhang (1997), highlighted operational change, availability, false alarm rate, maintenance requirement and cost as the key attributes or performance indicators of a good leak detection system and compared it among the different leak detection techniques. It was discovered that no method was rated “GOOD” for all the attributes, false alarm was also discovered to be the major problem for all the methods except biological and sampling method whose major problem lie in the fact that they cannot monitor a pipe continuously.

3.4.3.1 Leak Detection Methods

This section offers brief description of the various leak detection methods (as represented in figure 19) used to ensure the integrity of pipelines.

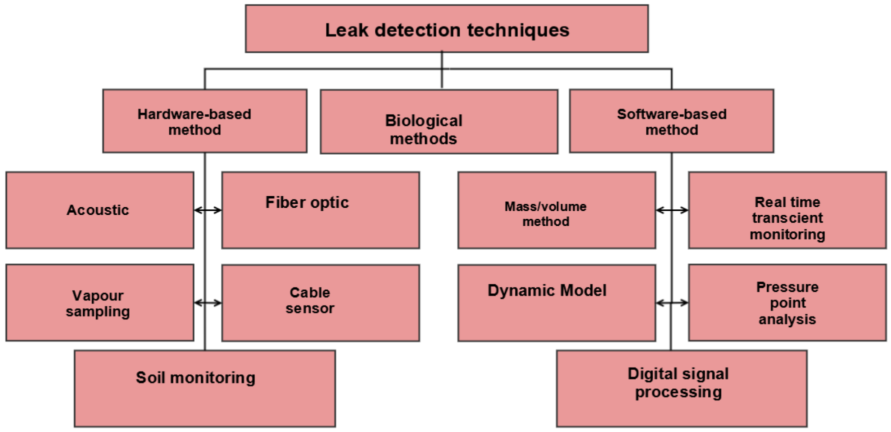


Figure 19: Classification of leak detection techniques

Hardware based leak detection methods

Some of the Hardware based pipeline leak detection methods are discussed below:

1. Acoustic sensor method: This method works on the principle of leak detection through the noise generated by leaks located outside the pipeline. When a leak occurs, low frequency acoustic signal is detected by the sensors. This is investigated, if such signal is different from the standard signal, an alarm is activated. The received signal is usually stronger near the leak which enables easy leak localization. This works best for high pressure, low flow-rate pipelines. Figure 20, is an illustration of acoustic sensor leak detection method. For better performance, the noise level around the pipeline is kept as low as possible. Because the noise level has to be low, this method cannot function properly for high flow rate scenario where the background noise shields the noise of a leak.

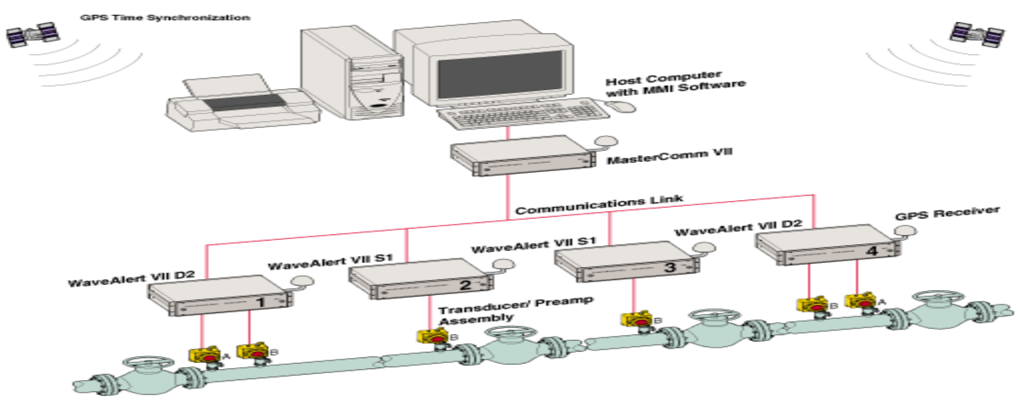


Figure 20: Acoustic sensor detection technique (wavealert.com)

2. Fiber optics sensor (FOS) method: These when buried parallel to the pipelines detect leaks through (i) the monitor of changes in temperature development (ii) development of micro bends in the immediate surrounding of the leak (iii) change in optical property of the distributed fiber when in contact with hydrocarbon (Scott and Barrufet, 2003). In figure 21, each fiber optic chain along the pipeline on the pipeline includes six different sensors and a single fiber optic cable connects the six sensors to the monitoring system.

Figure 21: Distributed fiber optic sensor along a pipeline (azosensors.com)

Fiber optics can be intrinsic or extrinsic depending on whether it is functioning as the information carrier or as the sensing element, it could be in the form of point sensor or distributed sensor along the many kilometers of the pipeline (Tapanese,2001) and has found application in various fields where it can detect a wide range of physical, mechanical, biological matter. The distributed FOS when used with optical radar technology (OTDR) has the capability of pinpointing the exact location of the disturbance or fault on a pipeline however, OTDR monitors only static or quasi-static effects on cables like sharp bends, fiber fracture, loose connections etc.

3. Soil Monitoring method: This utilizes an inexpensive non-hazardous gaseous tracer that is pumped into the pipeline. Such tracer is very volatile and escapes from the pipeline at the exact location of the leak (Golmohamadi, 2015). Tracer is added at a concentration of few parts per million to the pipeline contents and has no measurable impact on their physical property. Within a few weeks, tracers leak out of the pipe, these are dispersed by diffusion into the surrounding soil air and volatilizes immediately. With the help of

probes (or leak detection hoses for long pipes) that are placed in the soil near the pipeline, vapour samples are collected and hoses are analyzed for tracer with gas chromatograph.

Software based leak detection methods

Some software based pipeline leak detection methods are discussed below:

1. Mass/Volume balance method: This technique is based on the principle of mass conversion (Murvey and Silea, 2012). A leak is usually revealed when there is an imbalance between the input and output gas mass or volume (Liou,1996). The difference between the volume of gas existing in a section of the pipeline and that entering the same section is determined by measuring some commonly used process variables like volumetric flow rate, pressure and temperature and if it's above a certain threshold, a leak alarm is triggered off. For the software to utilize the variables they must be converted into mass flow rate or standard volumetric flow rate. This is the most widely spread technique in use and requires high accuracy of the instrument that measure flow pressure and temperature variables. It finds application in arctic and underwater environment.

2. Negative pressure wave: This method is based on the principle that when there is a leak in the pipeline, the pressure at that section of the pipe drops (Murvey and Silea, 2012) thereby generating negative pressure waves otherwise known as rarefactions that are propagated with a certain speed towards both ends of the pipeline. With the help of the two pressure sensors or transducers located at both ends stations of the pipeline, the negative pressure is recorded by the sensors (Silva et al, 1996) which then locates the leak by calculating the time difference between the arrival times of the negative wave at each end. The estimation of the time difference is done in a way that if the leak is closer to one end of the pipe, the transducer at this end will first receive the pulse, the amount of time needed to receive the pulse at the other end is used to detect the leak location with accuracy. Leaks can also be detected using pressure wave by a purposeful generation of transient pressure waves simply by opening and closing valves periodically (Elaoud and Hahj-Taieb, 2010), with the presence of a leak, the pressure waves are partially reflected, allowing the detection and location leaks.

3. Dynamic Model: This method uses mass momentum, energy and equation of state algorithms which are pipe flow models to determine the presence of leaks in pipelines. To minimize false alarm, noise level and transient events are continuously monitored (Scot and Barrufet, 2003; Golmohamadi, 2015). This method was discovered to be able to detect small leaks that are less than 1% of flow when (Siedert and Klaiber, 1980) tested it on a 68km gasoline pipeline. The result revealed that the detection of 0.2% of inlet flow was possible in 90 seconds. This method however is expensive (Sivathanu, 2003).

3.4.3.2 Pipeline Inspection

Since corrosion is inevitable, difficult to characterize in steel pipes and depletes metal (Cosham, Hopkins and Macdonald, 2007) there should be means of detecting the rate at which corrosion has depleted the pipeline. This is achieved by pigs. Figure 22, is the schematic diagram of a pig that has been launched into a pipeline for inspection purposes.

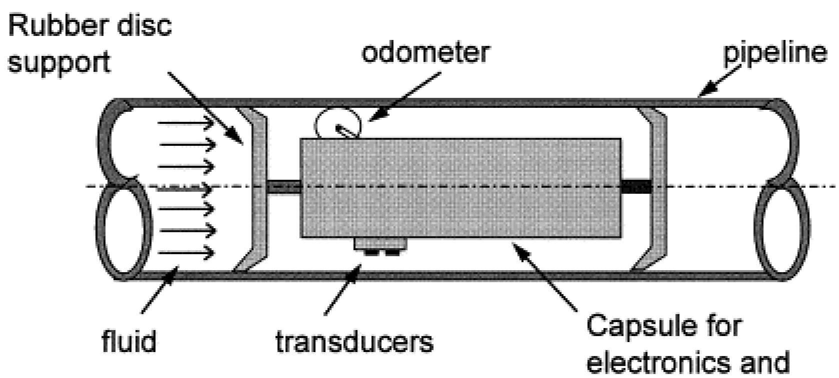


Figure 22: Schematic drawing of the pig inside the pipeline (Okamoto et al, 1999)

Smart pigs

These are cylindrical-shaped electronic devices used by the oil pipeline industries to detect the loss of metal and deformation in some cases (Kishawy and Gabbar, 2010). This when inserted into pipeline is propelled by the flowing fluid, recording certain physical data about the pipeline like the location of reduced pipe wall thickness, dents etc. The data recorded by smart pig is utilized by the pipeline operator in making effective decision on finding and mitigating potential problem area before they turn to real problem.

Over the years, smart pigs have evolved into three other specialized tools; namely: metal loss or thickness tools, crack detection tools and geometry tools. Depending on the inspection task, metal loss tools and crack detection tools are distinguished in the pipeline industry (Reber et al, 2002)

These are briefly explained below:

(1) Metal loss tools

These tools detect the exact location of metal loss along the pipeline. The metal loss tools are as follows:

(i) Magnetic flux leakage (MFL) is a tool that uses the induced magnetic field along the pipeline to locate and record magnetic flux anomalies as it travels along the pipeline. This can inspect the ferromagnetic pipelines while they are in service without the need of shutting down the pipeline (Mandache, Shiari and Clapham, 2005) and relies on calibration runs for correct interpretation of the leakage signals in terms of defect location, size and depth. The magnetic flux data recorded is converted to information which provides an indication of metal loss in the pipe. High resolution MFL and Standard resolution MFL are the two types of MFL.

(ii) Ultrasonic: While MFL provides qualitative pipe data, Ultrasonic tool provides quantitative results such as the extention and depth of defects with a precision of mm (Edelmann and Gribi, 1990) using ultrasonic technology. Also, known as UT tool, transmits an ultrasonic pulse into the pipe wall to detect the size and locate metal loss, cracklike defects in the body and welds of transmission pipeline (Reber et al, 2002). This is achieved through the measurement of the propagation delay time of an acoustic wave emitted by an ultrasonic transducer which travels in the medium and is reflected when the wave reaches the inner and outer wall of the pipeline (Okamoto et al, 1999). The distance between the transducer and the pipe wall which is used to evaluate the extent of internal corrosion can be obtained from the signal reflected by the inner wall while the evaluation of external corrosion is done using the time of flight between the echoes from the inner and outer wall.   UT tool's greatest problem lies in the fact that it requires a clean pipe wall for operation and so cannot be used for crude oil pipeline with paraffin build-up. Wall thickness limitation is another problem in the sense that it works well with heavy-walled pipes but not with thin-walled pipes and requires liquid propellant for it to operate efficiently which makes its application limited to only oil pipeline and not to gas pipelines and such is not widely used like MFL.

(2) Crack detection tools

These technologies though new and still developing are used for the detection of cracks along the pipeline. They include:

(i) Ultrasonic crack detection tools which work by the generation of ultrasonic signals into the pipe wall that is reflected off the internal and external surfaces of the pipeline. The signal is reflected along the same path of the tool when crack is detected. This tool can only be used for oil pipeline since there is a requirement of "liquid coupling" between the sensors and the pipe wall. In-line inspection technologies (ILI) using ultrasound has proven to be a suitable and reliable technology for crack detection in pipelines. The concept makes it possible to use the same tool for both crack detection and inspection and involves the straight incident (normal to the pipe surface) of ultrasonic pulses on pipe walls to measure their thickness and when the incidence is angled (at 45 degree) generates a shear wave through the pipe for crack detection (Reber et al, 2002). The major challenge of these tools lie in the fact that (depending on the pipe diameter to be inspected), it requires the control of several hundreds of sensors, their echo records and the application of on-line data processing to reduce the quantity of data and the resulting data that is finally stored. Ultra-scan crack detection tool has been developed by Pipetronix in 1994 for pipeline crack detection and has successfully inspected nearly 1000km of oil and gas pipeline (Willem, Barbian and Uzelac, 1996).

(ii) Transverse magnetic flux leakage tool magnetizes the pipe wall around its circumference to detect cracks for instance, longitudinal seems cracks and longitudinal seems corrosion. This functions in a similar way to MFL, the difference lies in the fact that the induced field is in a transverse or perpendicular direction. Its major disadvantage lies in the fact that cracks must have sufficient width before they can be detected and the crack severity is not determined.

(iii) Elastic wave tools work by sending ultrasound waves in two direction along the pipeline to locate and size longitudinally oriented cracks and manufacturing defects.

(3) Geometry tools

These tools which gather information about the physical shape or geometry of pipelines are used to find "outside damage" or dents in the pipeline, although they can detect and locate mainline valves, fitting and other appurtenances. They include: (i) Caliper tools which utilize set of mechanical fingers or arms that ride against the internal surface of the pipe or use electromagnetic methods to detect dents or deformations. (ii) Pipe deformation tools operate in the same way as caliper tools but use gyroscopes to provide the o'clock position of the dent or deformation in the pipe. This can also give information about pipe bend.

3.4.3.3 Integrated Operations (IO)

Integrated operations (IO) refer to work processes that allow for tighter integration of personnel that are involved as well as operators and service companies that work to plan, operate and maintain the oil and gas fields and their facilities, made possible through the use of modern Information & Communication Technology (ICT) and high bandwidth fiber optics network for real-time data sharing between remote locations (Rosendahl, 2012; Devold, 2013). IO been more of a revolutionary strategy aims at enhancing the integration and understanding between on- & off-shore organization resulting to faster and better decision making (since both parties have indebt knowledge of the situation of things). It has been known to be the earliest thought of e-maintenance (Crompton and Gilman, 2011). Figure 23, illustrates the different areas IO links together.

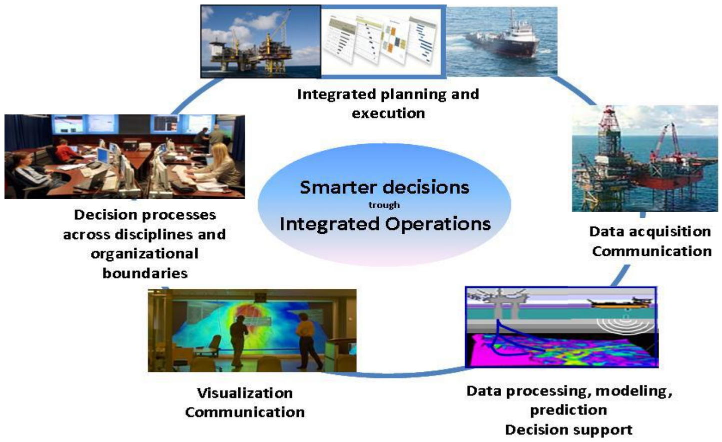


Figure 23: IO loop (IO research NTNU, 2013)

Four factors necessary for IO to be implemented were identified as follows:
(i)Advanced technologies that enhances the maintainability of assets (ii)Digital IT infrastructure that enhances reliable transfer and exchange of O&M data between different stakeholders (iii)Active operational networks lively connecting producer's O&M personnel and the personnel of engineering (iv)Business-to-Business (B2B) collaborative partnerships that lay the foundations to create a reliable information and knowledge network. Figure 24, is a schematic representation of the four factors necessary for integrated operations to take place in the oil and gas sector.

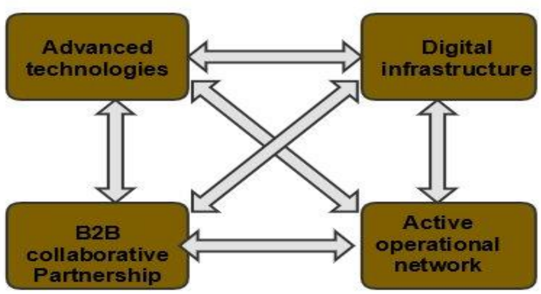


Figure 24: four-fold principal aspects of IO in O&M (Kobbacy and Murthy, 2008)

The successful implementation of IO for the monitor of oil and gas pipelines heavily depends on three important features which include:

1. The synergy between remote prognostics and diagnostics technologies

Prognostics and diagnostics technologies refer to technologies that are used for the real-time monitor of pipeline conditions. They are particularly the various inspection and monitoring technologies that have been discussed in the previous sections. With today's IO; using condition monitoring to support technical and safety integrity is enhanced since; (1) There has been a lot of improvement in data acquisition technique which enables experts to tap into real-time signals of critical equipment at offshore locations from Onshore Support Centre (OSC). (2) Combined interpretation and trend analysis has been enabled by online communication capacity.
(3) Technological capabilities that have been acquired by expert centers are used to secure connections to several offshore assets in such a way that such assets are served simultaneously if necessary. The success of integrated operations in the North Sea has been attributed to the use of advanced networking and communication technologies which have made it possible for offshore personnel to effectively communicate with OSCs allowing more sensible use of data acquisition technologies and this has in turn given a new dimension to diagnostics & prognostics efforts for North Sea assets today.

2. Collaborative video conferencing which connects onshore expert centers directly with onshore collaborative rooms

Onshore remote support centers (OSC) and virtual activities are the active nodes of integrated operation settings which are usually established at the O&G producer's premises and that of the third party organization. The OSCs at the O&G producer's end generally, have built-in communication capabilities with Offshore control rooms and external business partners while that of the third-party organization mainly serve to provide expert assistance in some areas like logistics, vibration monitoring. etc. on a 24/7 online & real-time basis. Technologies for remote monitoring, table top collaborative workstations, back projected large Visual Display Unit (VDUs), video conferencing facilities and other joint decision making technological capabilities are some common features of the these OSCs which help in active collaborative team work. The success story of Conoco Philips (which is an operator of Ekofisk assets, with two onshore centers) provided a very fruitful environment for rapid exploitation of technology (which includes CBM), shared -expertise, decision and work process optimization, multi-disciplinary co-ordination of planning (example between O&M and drilling). etc.

3. Net-based web enabled ICT solutions

The ICT solutions used range from more centralized LANs (Local area networks) primarily used within the organization, to a large-scale WAN (Wide Area Network) that opens transaction routes for complex B2B traffic. The North Sea is known for its use of large scale ICT network called SOIL (Secure Oil Information Link). SOIL which is an ICT-based active data exchange communication network (Liyanage et al, 2006) was introduced in Norwegian E&P in 1998 and was because of growing demands for integrated data management and B2B solutions. With its application that connects almost all business sectors of the Norwegian O&G industry; it has helped to establish connectivity and interactivity between different parties for instance; offshore O&M teams, operator's onshore O&M support groups, third party experts, logistics contractors. etc. Figure 25, illustrates the application of SOIL solutions in providing many -to-many connectivity on 24/7 online real-time to enhance D2D & D2A performance of O&M

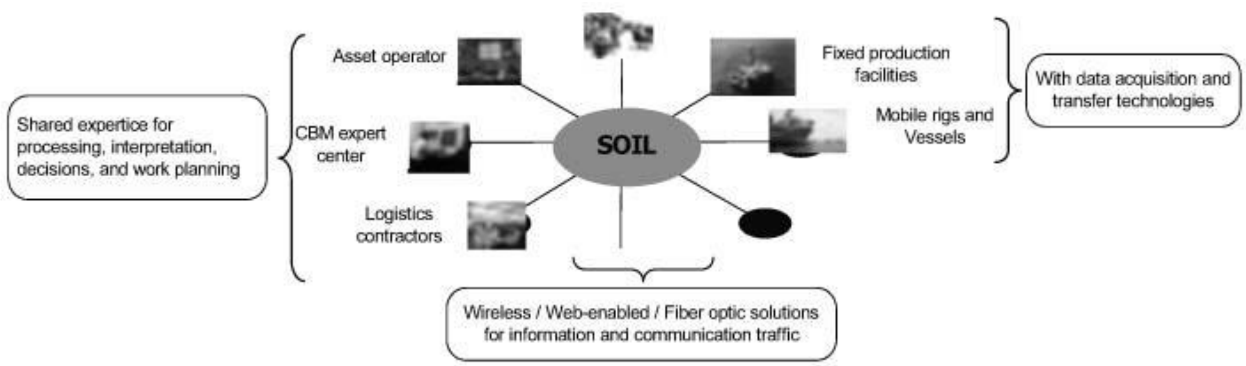


Figure 25: The application of SOIL solutions (Kobbacy and Murthy, 2008)

This connectivity is made using fiber-optic cables and wireless communication. With this, real-time equipment data can be acquired and jointly analyzed and the final exchange of results online between these parties results in a better shared interpretation and decision making.

3.4.4 The Mindset or Paradigm out of which the Pipeline Arises (The Fourth Leverage Point)

Among the many integrity threats to oil and gas pipelines, vandalization has been recorded as one of the major systemic risks to pipelines in developing nations like Nigeria (Adebayo and Dada, 2008; Onuoha, 2009), this could be attested to, by the numerous reports of vandalism incidents and related fire disasters which involved 2787 pipeline incidents reported in 2011 of which 2768 incidences were as a result of vandalism (Ambituuni et al, 2013). This has been attributed to many factors which are to be explored in this section likewise the numerous stakeholders involved in this menace.

3.4.4.1 Conceptual Overview: Pipeline Vandalization

Pipeline Vandalization as used in this work refers to the illegal or unauthorized act of destroying or puncturing of oil pipelines either for disrupting supply or to siphon crude oil (or its related products) to appropriate it for personal use or for sale on the black market or any other outlet (Onuoha, 2009). From this definition; oil bunkering, breaking of oil pipelines to siphon fuel, fuel scooping from burst pipelines and deliberate acts of oil terrorism are all acts of vandalism. Pipeline vandalism or interdiction as used by Church, Scaparra and Middleton (2004) has been reported in many countries of the world both developed and developing nations (Hosmer,1995) and this often resulted in great spills occurring in hard to reach areas. A brief look at the different acts of pipeline vandalization is taken below:

1. Oil bunkering

   The term oil bunkering as used in the Nigerian context is a kind of oil theft which involves tapping crude oil directly from pipelines or well heads (Asuni, 2009; Human rights watch, 2003). This act is carried out by perpetrators by building an enclosure around a section of the pipeline that transports crude oil which is located away from the oil company facilities. To be able to drill a hole on the steel pipeline, water is pumped out of the enclosure which gives room for the drilling of the hole and then the hole is fitted with pipes and control valve (Onuoha, 2010) and the creek water is pumped back into the hole thereby covering the set up and hiding it from the oil companies' inspectors. When crude oil is pumped through pipelines at great pressure, the bunkers fill up to 1000 metric ton barge in a matter of hours (Junger, 2007). From there, the oil is placed in small barges and taken out to the sea, where it is loaded unto large ships hidden out of sight of the authorities. The bunkerers in return receive money and weapon whereas the crude oil is taken to spot markets such as in Rotterdam or refineries in some other countries like Cote d'ivoire (Asuni, 2009).

2. Fuel Scooping

This like all other vandalism acts on pipeline, has its main target on pipelines conveying premium motor spirits commonly known as petrol or fuel. This act, although minor and usually conducted by the local people involves the small-scale pilfering of condensate and petroleum products that are destined for the local market (Asuni, 2009). Some of these products if unrefined are taken to the local refineries where they are processed into finished products. This act of vandalism has a remarkable growth in recent years in Nigeria, with its early beginnings in the early and mid-1990s when the vandals were mainly unemployed youths in remote area and communities who puncture pipelines that pass through their communities (with drilling tools) or took advantage of ruptured or leaking pipes to siphon products into drums, plastic containers or storage cans for sale on the black market. Then the rate of vandalism was very low and the technology that was used for vandalism were very rudimentary for instance, use of funnels, drilling tools, plastics to siphon products. Only seven cases were reported (Onuoha, 2010).

The next trend saw the increase in sophistication of technology used by the vandals and more complicity among various stakeholders like oil marketers, politicians, security agents and NNPC staff. These was learnt from the confessions that were given by captured vandals who mostly confessed how security agents and Chief complied with them to carry out the act. This happened with the return of democracy in 1999 such that 497 cases that was reported in 1999 skyrocketed to 909 cases in 2000. Although there was a decline between 2001 and 2003, it later rose to 971 cases in 2004 and then with a sharp increase in 2005 to 2258.

3. Oil Terrorism or sabotage

   This involves illegal use of force or violence against oil pipelines or facilities to intimidate or coerce the government in pursuit of political or social objective (Hosmer,1995). Oil terrorism was used by analysts and scholars to describe the deliberate attack on pipeline systems in Iraq and some other parts of the world where there were political unrests by militia, freedom fighters and insurgents. All acts of blowing up pipelines, installations and platforms with explosives and the seizure of oil barges, oil wells, flow stations, support vessels and some other facilities to prevent the exploration and/or distribution of crude oil or its products are all categorized under pipeline terrorism in Nigeria.

3.4.4.2 The Niger Delta region: A Brief Background (Human and National Security)

The Niger Delta region of Nigeria is a geopolitical region with the highest oil and gas production capacity in Nigeria. It is one of the world's largest wetlands and the sixth largest exporter of crude oil being notorious for its environmental pollution, poverty and violence (Ifeka, 2001; Wilson, 2014). Figure 26, is the map of Nigeria showing the different states that make up the Niger delta region of Nigeria while figure 27 represents the different pipeline routes in this region.

Even though oil and gas resources from this region accounts for over 90% of Nigerian export and foreign exchange earnings and over 70% of total Nigerian revenue (Odalonu and Eronmohonsele, 2015; Malumfashi, 2008); with its diverse ethnic group (which is classified as the minority ethnic group in Nigeria) (Owolabi and Okwechime, 2007); the level of poverty here is more than the national average and the gap between the "haves" and the "have nots" is more pronounced in this region.

Figure 26: Map of Nigeria showing the different states that make up the Niger delta region of Nigeria

This is because of years of neglect by the government coupled with the high rate of environmental degradation caused by the operations of multinational companies in the region without regard to the effects on the rural population.

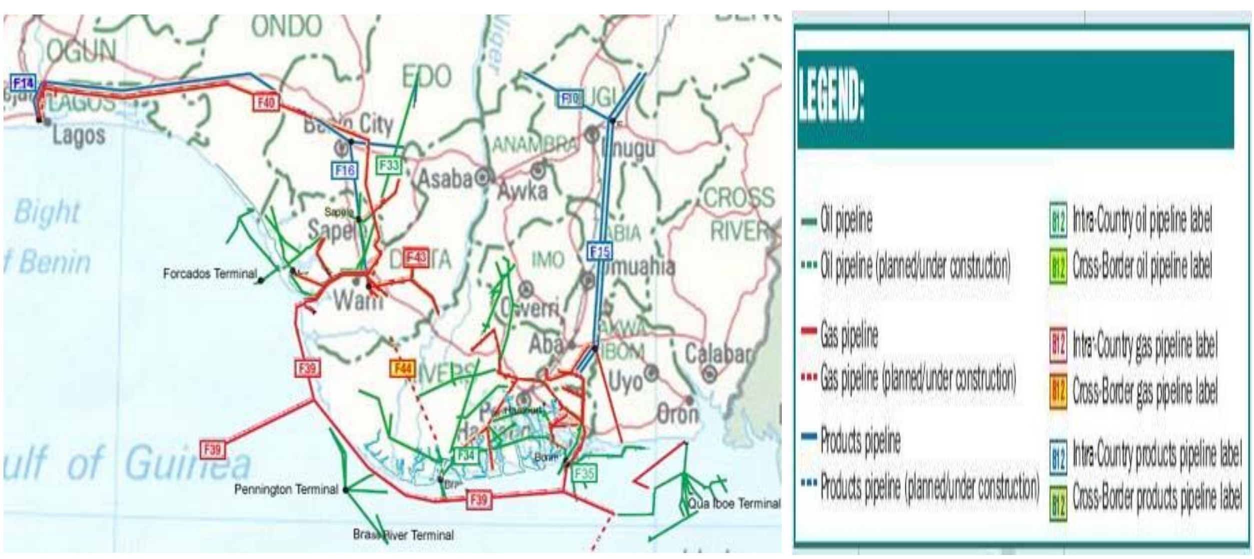


Figure 27: Map of the Niger delta region showing the different pipeline routes in the region

Because oil spills and gas flaring are frequent occurrences in this area, they constitute the most serious forms of environmental degradation which usually inflict serious human, environmental and socio-economic hardships leaving behind permanent damage to farmlands, soil and water (Gbadegesin, 1997; Celestin, 2003). The impact of these permanent damages left behind by the oil spills in this region are well documented by (Frynas 2000; Esparza and Wilson 1999; Junger, 2007; Human rights watch, 1999) while that of gas flaring is also well documented by (Junger, 2007; Esparza and Wilson, 1999 ; Human rights watch,1999). According to Junger (2007), two and a half million barrels of crude oil were spilled or leaked into the riverine environment between 1986 and 1996 which resulted to the wholesome devastation of fish stocks that most villagers rely on, also gases that are flared in this region result in blighting acid rain and these tend to contaminate the well water which having been polluted with hydrocarbons, no longer becomes fit for human consumption but people still take them.

Also, the Niger Delta community has suffered serious negligence from the government, starting from the negative effect of their exclusion from oil-based federal and state power while being subordinated to the dominant political class, the high illiteracy level in this region, the fact that some of the states here have no connection to the national electric power grid to the poor infrastructural development in the region etc. (Ifeka, 2001). Meanwhile, the urban development that is experienced in the major cities of Nigeria can be traced to the oil wells located in the remote villages of the Niger delta region where oil continues to gush out day and night (Taiwo and Aina, 1991). The skyscrapers, good roads and other physical infrastructures that are enjoyed in the cities could be traced back to the villages where this oil is ever pumping with a sad tale full of sound and fury signifying poverty and neglect. The oil that was supposed to be a blessing has turned into a curse which means poverty, hunger and diseases. To them, it now means undiluted suffering, bare -faced deprivation and capitalist exploitation, the magnitude of which is being compared to what happens to a cow in the hands of the selfish dairy man who is only concerned with the milking of the cow dry and caring less about the cow’s well-being, disposing it when the milk has gone dry (Owolabi and Okwechime, 2007).

From the level of environmental degradation that are experienced here, it is abundantly clear from the activities of these multinationals, that they are a big threat to the very existence of the oil-producing communities. With the grossly polluted and degraded environment, farmers and fisher folks, find it so difficult to eke out a living. A consequence of this, as the events have shown in the Niger delta simply means that the Nigerian state is more concerned about the security of oil production and the safety of oil installations, than it is for the security of the inhabitants of the region and their well-being (Owolabi and Okwechime, 2007). This of course, heightened the sense of insecurity of this people as their sources of livelihood are continuously being put under great threat by the day. With the frustration caused by the indifference of the Nigerian government and the arrogance of the oil corporations, these communities gradually mobilized for a non-violent showdown with the state and the oil multinationals operating in their region. The companies' response to such non-violent showdown was to request for the presence of the notorious and much dreaded mobile police popularly known as "kill and go" under the pretense that it was under imminent attack. This saw the attack on peaceful protesters by the mobile police team with tear gas and gun fires. As if that was not enough, they returned the next day and laid waste the community meanwhile the protest was non-violent according to enquiries that were later carried out on the issue (Owolabi and Okwechime, 2007).

It is against this backdrop that some opposition groups like Movement for the survival of the Ogoni people (MOSOP) emerged. The judicial murder of MOSOP leaders in 1995 along with their kinsmen, saw a great increase in the level of animosity against the government and the multinationals by the people of this region and this brought into focus the national security challenge that confronts the Nigerian state today. These challenges are most evident in the ease with which irate community youths disrupt oil company's operations, frequent attacks on oil and gas installations and pipelines, hostage taking of oil company workers most especially top expatriates followed by the demand of ransom, oil-bunkering, oil-scooping and worst of all oil terrorism. This crisis has continued despite the state's repressive interventions leading both the state and the oil multinationals to report huge revenue losses.

3.4.4.3 The stakeholder view of Niger delta oil and gas pipelines

Since internal (system) change cannot fully account for the integrity threats of pipelines most especially as it regards vandalization, one should look beyond the system and focus on external change. External change is the emergence of new groups, events and issues which cannot be readily understood within the framework of an existing system, model or theory (Freeman 1983).

One possible approach to the conceptual problem of dealing with this external change is to redraw the oil and gas pipeline boundary as represented in figure 28, which considers all those groups and individuals that can affect or are affected by the oil and gas facilities. These we call the stakeholders of the oil and gas facilities. According to Freeman (1983), a stakeholder is a person or group of individuals who can affect or are affected by the accomplishment of an organizational purpose or system purpose.

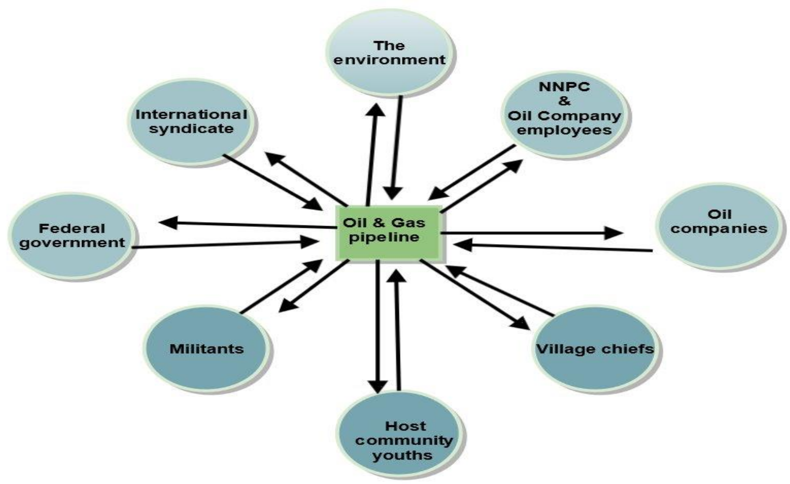


Figure 28: Stakeholder view of an oil and gas pipeline (The developing country –Nigeria Case)

The sheer number of players involved in vandalization illustrates how complex oil theft issue is in Nigeria. It is a multidimensional activity cutting across sheds of people both locally and internationally (Odalonu and Eronmohonsele, 2015). Three levels of stakeholders or actors are easily visible when it comes to pipeline vandalization and oil theft (Asuni, 2009) and then the environment. They include:

1. Local Level

   The actors at this level vandalize oil facilities, installing illegal taps thereby siphoning the oil from well heads and manifolds (Wilson, 2014). These include, local gang groups, militants, security agents, village chiefs, host community etc. Vandalism and oil theft at this level is enhanced by the hidden location of pipelines and installations which are more to the interior parts of the community making it difficult for both oil multinationals and the security personnel to provide adequate security for the facilities. Also, there is much complicity among the various actors in this level. There have been allegations of complicity between oil marketers, traditional rulers, security agents and the Nigerian national petroleum cooperation (NNPC) staff (Onuoha, 2009). The locals handle the tapping of crude oil which is refined using local technology after which the products are consumed and marketed along Nigerian streets as cooking fuel, gasoline and diesel (stakeholder network, 2015).

2. The Senior Echelons

   As one moves up the network, the actors here are basically members of the Nigerian military, the oil company and NNPC employees, top politicians and retired military officers (Asuni, 2009). At this stage, the host community youths and militants provide the local manpower, the oil company personnel provide the technology for opening oil wells and pipelines while the security agents provide security for their operation (Odalonu and Eronmohonsele, 2015).

3. International Level

   This consists basically of foreign partners who provide the markets and the shipment of stolen oil oversea in exchange for either weapon or hard currency. At this level, countries from Eastern Europe, Russia, Australia, Lebanon, Netherlands, France, Senegal, Cote d'voire etc. are all involved. According to Asuni (2009), crews of two bunkering ships; one Filipino and another Ghanaian that were arrested in Nigeria shed some lights into this hidden syndicate.

4. The environment

   The oil and gas facility environment includes, living components like humans, animals, plant etc. and non-living components like the air, water bodies, soil, rocks etc. Anything that enters an ecosystem or the environment from sunlight to rain can contaminate it and has the potential to change it. Human actions have been known to greatly impact the ecosystem. Oil and gas pipeline vandalization and some of the operations of the oil companies have continuously degraded the host communities' environment with its corresponding negative effect on the human population. The barrels of oil that are spilled on lands and water bodies, inflict human, environmental and socio-economic hardships on the affected communities with long term or permanent damage to farmlands, water bodies, soil and fish farms (Gbadegesin, 1997; Stakeholder democracy, 2016; Human rights watch, 1999). On the other hand, the gases that are constantly flared by these companies pose serious threat to the environment. Approximately 75% of the total gas production in Nigeria is flared and this puts Nigeria as the highest gas flaring country in the world (Human rights watch, 1999 pg: 65; Malumfashi, 2008). These come with their corresponding long term effects on humans, animals and the environment due to the enormous heat, noise, vibration and eternal flames that are generated by gas flaring (Owolabi and Okwechime, 2007). The climax of this results in acid rain which induces the destruction of roofs, fresh water fishes and the forest of the host community.

3.4.4.4 Historical Factors Leading to Pipeline Vandalization in the Niger Delta region

It could be seen that the problem of pipeline vandalization goes beyond the system boundary and encompasses the environment around the system, in the sense that a lot of stakeholders are involved which range from local to international. Many contributing factors have been linked to the incessant oil pipeline vandalization in Nigeria, among which are poverty, high unemployment rate (mostly among the youths), international market for stolen oil, influence of arms and gang groups in the Niger delta region, collaborations between stakeholders involved i.e. security agents, government and oil multinationals; weak Nigeria legal framework and persecution process, emergence of barons and godfathers, defective security apparatus, official negligence (Wilson 2014; Onuoha 2009). From the Niger delta brief history, it is induced that the main problem of the Niger delta region could be linked to the “Frustration-aggression -theory propounded by John Dollard in 1939 (Best, 2006; Gatung, 1990). This theory postulates that violent behavior is caused by the inability of the actor to fulfil his/her socio-economic needs. In a simpler term, it means that where people’s expectations do not meet actual need, they tend to get frustrated and confront those they perceived as responsible for their frustration (Etekpe and Okolo, 2010). Linking the theory to the Niger delta case, we see that the people of the Niger delta region had high expectation from the multinational oil companies (MNOCs) when oil and gas were discovered in Oloibiri Bayelsa state in 1956. Their expectation was that this would help improve the social amenities, bring infrastructural development etc. as seen in some European countries where oil discovery transformed the standard of the common man. They protested from the nineties and got to the extent of vandalizing pipelines to express their anger and frustration at the activities of the MNOC and the level of underdevelopment that was experienced in the region. Such frustration was induced by the MNOCs and the federal government. The climax of this is seen in the formation of militant groups (organizations) to apply unconventional methods as a way of expressing their anger (Etekpe and Okolo, 2010). Another induced- frustration-aggression can be traced to issues of resource allocation and distribution where the revenue realized from oil and gas exploration is used to develop other regions making them richer and improving their standard of living whereas the Niger delta region which is the source of the oil remained in total neglect with high level of poverty and environmental degradation.

3.4.4.5 Interventions/ Recommendations

1. Addressing the economic, social and political problems of the Niger delta

The Nigeria government must work hard to address the socioeconomic grievances of the people of this region because doing so will remove any justification they might have for turning blind eye to the nefarious activities of criminals in their midst since the rise in trade of stolen oil can be traced to the neglect of the people of the Niger delta region. These people having received few benefits from the oil that lies beneath them see other regions being developed whereas they are left undeveloped and in abject poverty. This results in fight for control over this precious resource giving rise to vandalization, sabotage, ethnic rivalry and long-running insurgency. As if the poor developmental activities in this region is not enough, the people still have to contend with the destruction of the environment and their source of livelihood by so doing they are unlikely to vice out their disapproval when leading militants like Asari-Dokubo justifies his bunkering activities as an attempt to claim what is rightfully theirs.

2.Provision of legitimate employment

The use of local youths in building infrastructures not only brings development to the region but also keeps the youths gainfully employed. By so doing, no foreign companies would be there to harass. The provision of viable work opportunities in the oil and gas sector by the government will help reduce the allure of people into illegal activities. The government should as well show faith in the Niger delta people by awarding oil contracts and blocs to competent local community indegenes.

3.Monitor of coastlines and use of good surveillance technique

The government of Nigeria should ensure adequate monitor of coastlines and pipelines as well using surveillance equipment. Relatively cheap can be adopted to monitor attacks on pipelines and track movements of suspicious cargo around the Gulf of Guinea. The indigenes of the local community should be encouraged to secure pipelines passing through their community and be encouraged to report any suspicious activities going on around pipelines situated in their community. The intelligence gathered from surveillance equipment should be made public to shame the individuals involved while publicizing the intelligence gathered of suspicious ships will help shame the countries involved.

4.Aligning with other countries to crack down illegal deals

Nigeria should take the lead by taking tough actions domestically against oil bunkering and then encourage other countries to do same by making it clear to its international partners that accepting stolen crude from the Niger delta is prohibited. The Nigeria government can set up legitimate oil export contracts with countries like Cote d'voire who have previously benefitted from stolen oil deals.

5.Strengthning of the Nigerian military and other security outfit

A total reform in the security should be carried by the government. Such reform should be introduced in all aspects, both operation, training and payment.

6.Adequate monitor of the operations of oil and gas companies and quick response to oil spillage and pipeline vandalism

The operations of oil and gas companies should be regulated and checked to guard against the gross environmental pollution that is always the result of their operation in the Niger delta region. Proper sanctions and fines should be given to such companies polluting the environment and quick response should be given to situations where the oil has already been spilled or pipeline has already been vandalized to prevent further damages to the environment.

4 Results and Analysis

This section covers the failure mode analysis of oil and gas pipelines carried out in four major Niger delta states namely: Rivers state, Akwa-ibom state, Delta state and Bayelsa state.

4.1 Oil and Gas Pipeline Risk Analysis

Risk has been defined as the probability of occurrence of a damaging event and involves the multiplication of the event with its severity or consequence (Liu, 2003; Khan and Haddara, 2003). Although it has been established that pipelines are the safest means for oil and gas transportation (Kishawy and Gabbar 2010; Papadakis, 2000) having lower accident frequencies than other means of transportation, various factors can lead to its failure which poses great risk to humans, natural habitat and the entire environment. Risk analysis or assessment which is a systematic and scientific way of predicting and preventing the occurrence of undesirable events by qualitative and quantitative information gathering of causes, consequences and likelihood of adverse events (Shariar, Sadiq and Tesfamariam, 2012) becomes very necessary. Oil and gas pipelines are assessed either qualitatively or quantitatively. While the qualitative method uses index system to assess risk based on the basic data (like pipeline length, population, flow rate, external interference etc.) of oil and gas pipeline with a qualitative risk value as the outcome, the quantitative method assesses risk by numeric simulation involving quantitative calculation of possibilities and consequences of different accidents whose outcomes are individual and societal risks Han and Weng (2011). Event tree analysis (ETA), Analytical hierarchy process (AHP), Fuzzy logic (FL), Fault tree analysis (FTA), Data Envelopment Analysis (DEA) have been devised for both qualitative and quantitative risk assessment Khan and Abasi (2001).

The analysis of risk for oil and gas pipelines in Nigeria for this work is done using the bow-tie analysis. This is a probabilistic technique that analyses the different accident senarios in terms of assessing their probabilities and pathways (Dujim, 2009). It maps the relationship between causes and consequences of an undesired event which it tries to prevent (Shahriar, Sadiq and Tesfamariam, 2012) and comprises Fault tree (FT) part on the left and Event tree (ET) part on the right. The FT part starts with Top-Event (TE) and diverges to the Basic Events (BE) using logic gates (AND & OR gates) while the right side is the Event Tree (ET) development which is the initiating event and follows sequences of event (consequences) until the possible events are reached. Figure 29, illustrates a typical Bow-tie diagram for oil and natural gas pipeline.

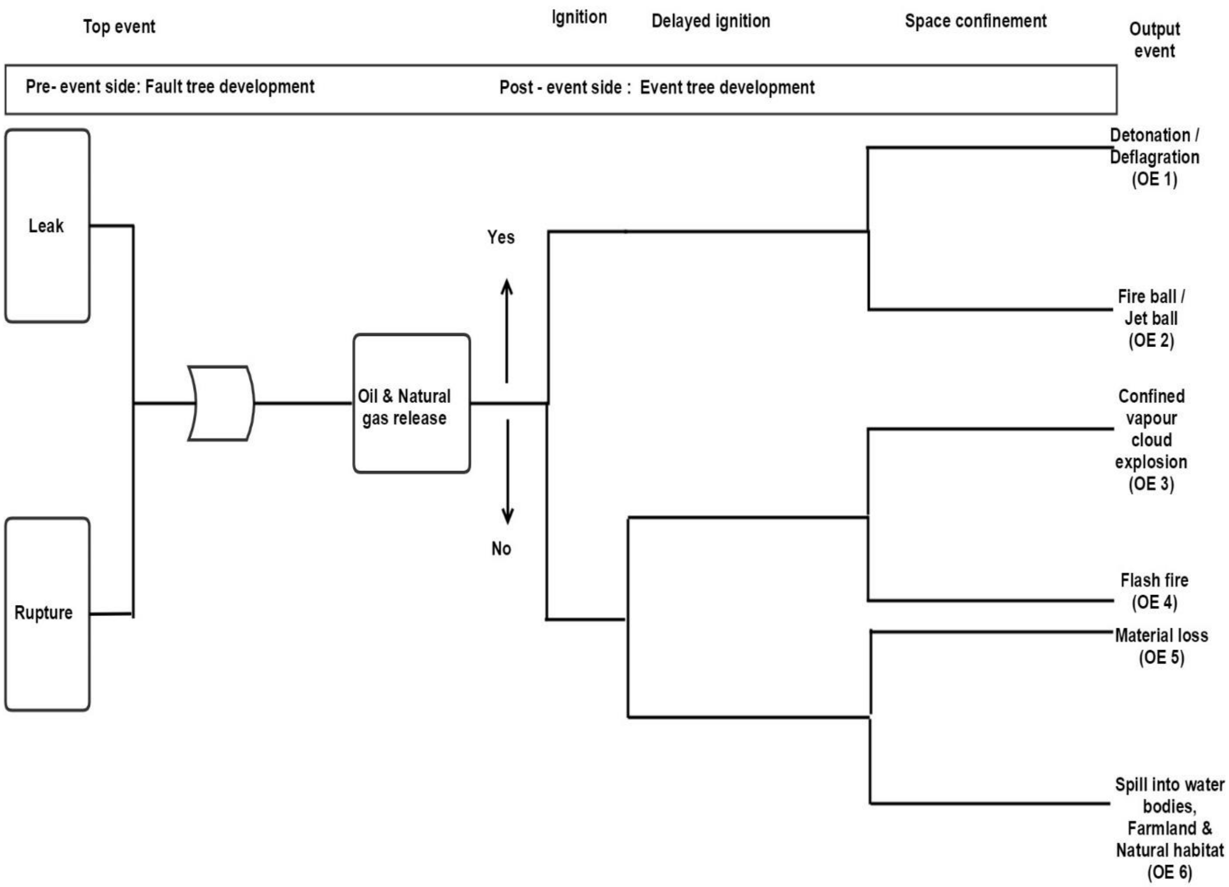


Figure 29: Bow tie diagram for oil and natural gas pipelines in Nigeria (ET part was modified after Shahriar, Sadiq and Tesfamariam, 2012) to incorporate oil pipelines as well.

4.2 Fault Tree Development

To be able to assess the risk due to oil and gas release from oil and gas pipeline in Nigeria, the main failure factors and the different sub-factors were identified as well as their probabilities of occurrences as presented in table 4. The oil and gas pipelines under study were divided into segments based on the state where they are located in the Niger delta region. The various information and history of the pipeline were collected. The flow chat in figure 30 was adopted to estimate the failure probabilities of the factors responsible for oil and gas pipeline failure in Nigeria.

Table 4: Pipeline failure factors and their respective probabilities across four Niger delta states in Nigeria.

Top event (TE)	Probability 1	Basic events (BE)	Probability 2	Bayelsa state	Rivers state	Delta state	Akwa ibom state
External interference	0.327	**Civil works**	0.098	0.0122	0.0490	0.0348	0.0020
		Sabotage	0.175	0.0438	0.0542	0.0559	0.0211
		Agricultural activities	0.054	0.0133	0.0152	0.0235	0.0020
Incorrect operation	0.248	**Incorrect process conditions**	0.092	0.0260	0.0200	0.0260	0.0200
		Maintenance deficiencies	0.156	0.0580	0.0390	0.0330	0.0260
Defects	0.132	**Manufacturing defects**	0.038	0.0095	0.0095	0.0095	0.0095
		Construction defects	0.040	0.0100	0.0100	0.0100	0.0100
		Operational defect	0.054	0.0135	0.0135	0.0135	0.0135
Corrosion	0.293	**Internal**	0.133	0.0343	0.0343	0.0277	0.0367
		External	0.160	0.0422	0.0406	0.0367	0.0406

These factors contributing to oil and gas pipeline failure in Nigeria range from design through maintenance to environmental issues. They are basically grouped into two parts, leak (Corrosion-internal and external) & (defects- initial and operational) and rupture (external interference - construction digging, sabotage)and (incorrect operation- operation and maintenance) (Dawotola et al, 2009; Shahriar, Sadiq and Tesfamariam, 2012; Hang & Weng , 2010). These factors were identified and used to develop the fault tree as presented in figure 31. The pipeline information used were : (1) The purpose of the pipeline which tells the type of fluid being conveyed by the pipeline (2) The year of pipeline commission (3) The type of coating applied on the pipeline (4) The diameter of the pipeline segment under study (5) The design pressure of the pipeline .etc.

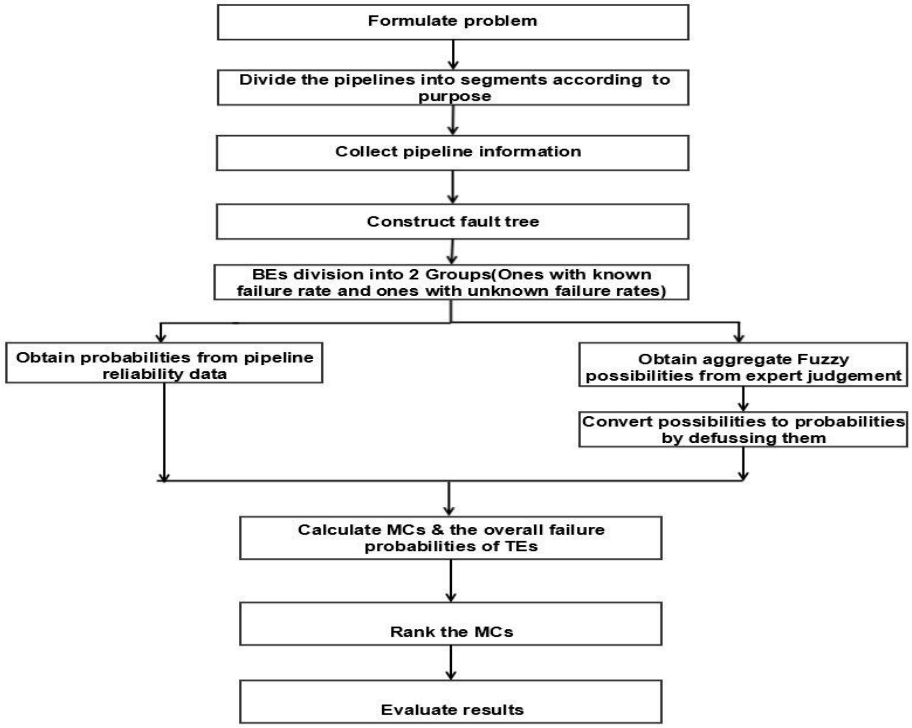


Figure 30: Flow chat for oil and gas fuzzy fault tree analysis (Adapted from Lavasani et al, 2016 and made to suit the purpose of our work)

Having completed the fault tree, failure probabilities were assigned to the BEs and this was done from three ways as recorded by (Lavasani et al, 2016): (1) From already established failure rates (2) From pipeline data sources in this case from incidents recorded in Nigeria daily newspapers (3) From expert judgements who have experience with oil and gas pipelines in the Niger delta region. (Shahriar, Sadiq and Tesfamarian, 2012; Lavasani et al, 2016; Dawotola et al, 2009; Yuhua and Datao, 2005) elaborated the use of expert judgement to obtain fuzzy possibilities or numbers which are finally converted to probabilities of BEs while Hang and Weng (2011) used index system in obtaining the probabilities of BEs.

The probabilities of the different BEs are as presented in table 4. Having obtained the failure probabilities of BEs, the probabilities of top events were obtained according to equation 1 (Lavasani et al, 2016)

$$P(T) = P(MCS_1 \cup MCS_2 \cup \ldots\ldots\ldots\ldots\ldots \cup MCS_N)$$
$$= P(MCS_1) + P(MCS_2) + \ldots\ldots\ldots\ldots P(MCS_N) - P(MCS_1 \cap MCS_2) + P(MCS_1 \cap MCS_3) + \ldots\ldots\ldots P(MCS_i \cap MCS_j \ldots\ldots)..$$
$$+ (-1)^{N-1} P(MCS_i \cap MCS_2 \cap \ldots\ldots\ldots \cap MCS_N) \ldots\ldots\ldots\ldots (1)$$

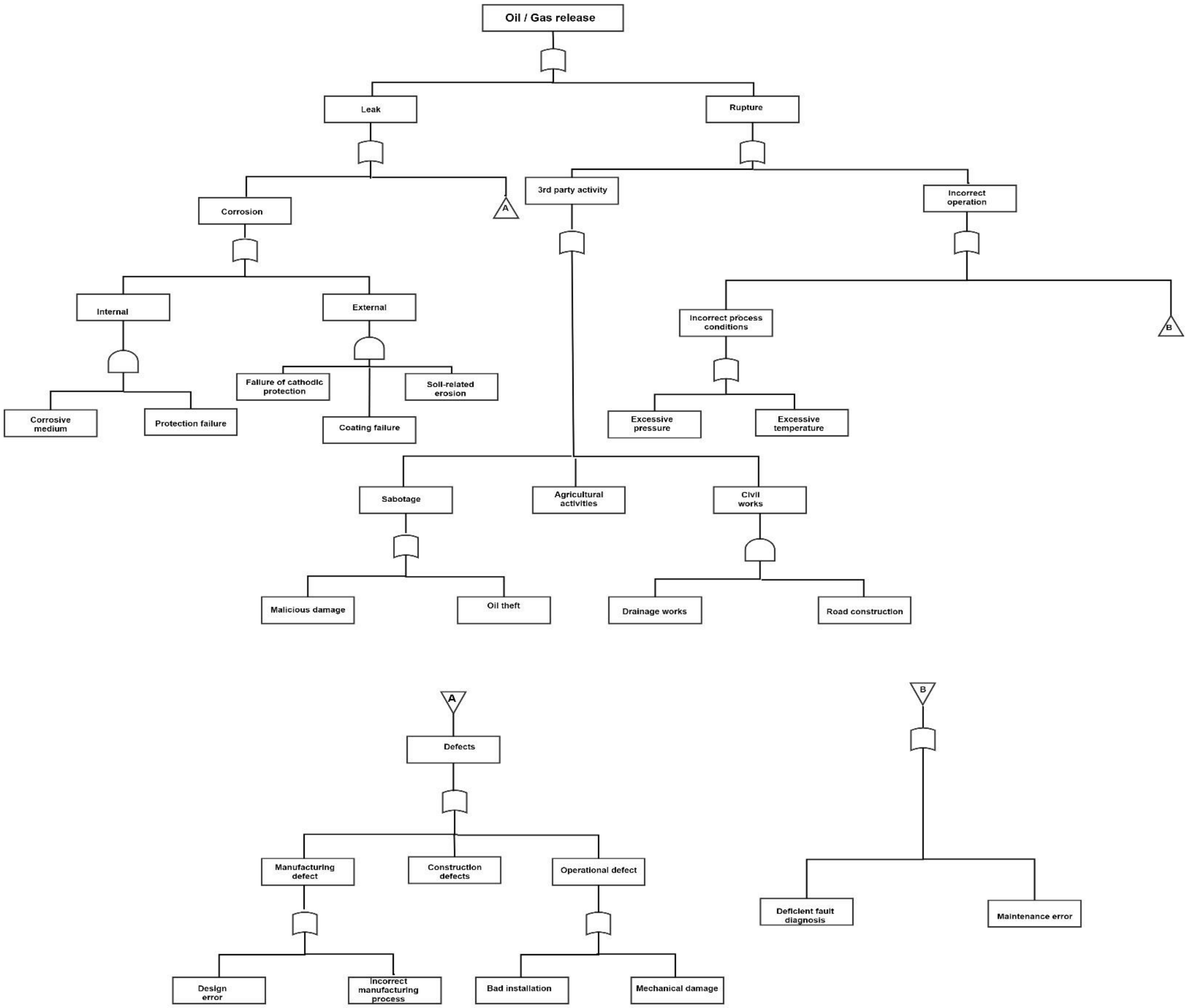


Figure 31: Fault Tree Analysis for oil and gas pipelines in the Niger delta region of Nigeria.

From table 4, the relative ranking of these factors were done and the result is as presented in figure 32. External interference was the most predominant oil and gas pipeline TEs, contributing 33% of all the pipeline failures. Of all the external interference BEs, sabotage is the most prevalent BE contributing 53.52% of all external interference BEs. Corrosion was the second most prevalent TE, contributing to 29% of the total pipeline failures in the country. Incorrect operation ranked third with 25% while defects is the lowest having a record of 13%.

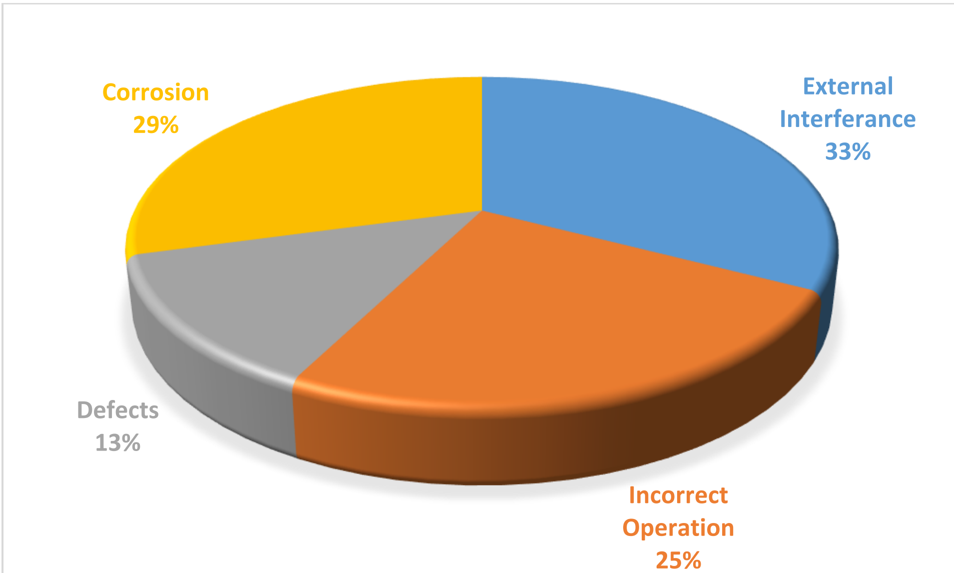


Figure 32: Percentage distribution of factors responsible for oil and gas pipeline failure in the four Niger delta states of Nigeria.

4.3 Event Tree (ET) Development

Many accidents arise from the release of oil and gas from a failed pipeline. This is because of the combustible nature of the fluid being conveyed by the pipelines which poses serious threat to humans and the environment near the failure location. This also comes with a lot of social unrest and national security issues in some developing countries, Nigeria for instance.

Event Tree(ET) which is a logic sequence that graphically portrays the combination of events and circumstances in an accident sequence, beginning with an initiating undesirable event and tending towards a result or account (Sklavounous and Rigas, 2006) is used to analyze the outcome events of oil and gas release from failed pipelines in the Niger delta region of Nigeria.

For this study, ETs proposed by Sklavounous & Rigas (2006); Shahriar, Sadiq and Tesfamariam, 2012 were adopted with some modifications made to incorporate oil release from pipelines. The right-hand side of figure 25, comprises events taking place after oil and gas have been released from pipeline. These events have been divided to take care of the time gap between gas leakage, possible ignition and space confinement produced by the surrounding with binary situations denoted as Yes (Y) or No (N), true (T) or False (F), Success (S) or Failure (F) to propagate the event until the outcome is reached (Shariar, Sadiq and Tesfamariam, 2012).

The tree on the right-hand side shows all the possible outcome of events that results when there is immediate ignition of oil and gas that were released. When this happens, gas clouds mixing with atmospheric oxygen is usually limited, so the ignition happens at the outer layer which is still within flammable limits while the inner core of the cloud is too rich with fuel for it to ignite. As the burning continues, the buoyancy force of the gas begins to dominate thereby becoming more spherical in shape and apparently turning into fire balls. This causes more mixing of the gas with oxygen thereby causing more gases to get to their flammable limits and sustaining the flame. Such fireballs are known to travel for miles until they are fully burned out.

However, when there is a delay in the ignition, there's a thorough mixing of oxygen and fuel which results to a faster burning cloud which burns from inner to outer layer. This sufficiently mixed oxygen and fuel burns faster with a medium pressure. Such subsonic burning is termed *deflagration* and it is only possible when the fuel-air mixture is within flammable limits.When there is space confinement, the rate of mixture increases and the flame propagates at a supersonic velocity developing a strong shock wave in the cloud which is characterized by abrupt high over pressure front resulting in a blast (Philips, 1994). Such explosion in which a shock wave is produced is termed *detonation*. The mixture exploding in confined space is termed *confined vapor cloud explosion (CVCE).* When there is very poor or very rich fuel mixture which are still within flammable limits, the flame front travels in the cloud in low velocity which results in insignificant pressure increases. Such phenomenon is termed *flashfire.* For the case of oil release, a delay in ignition leads to the spilling of oil on farmlands and water bodies that are close to the pipeline and the natural habitats.

4.4 Consequences

Several consequences arise from the release of oil and gas from a pipeline after an incident has occurred. Such consequences pose threat to human life, national security in developing nations, causes social instability, environmental damage, financial losses etc. These consequences are investigated in the hazard zones of the output events during and after release. A hazard zone is a region in which output events exceed critical threshold values and lead to negative effects for people, environment and property (Dziubinski, Fratczak and Markowski, 2006). Figure 33, represents a hierarchical framework for the consequences of output events in the Niger delta region of Nigeria.

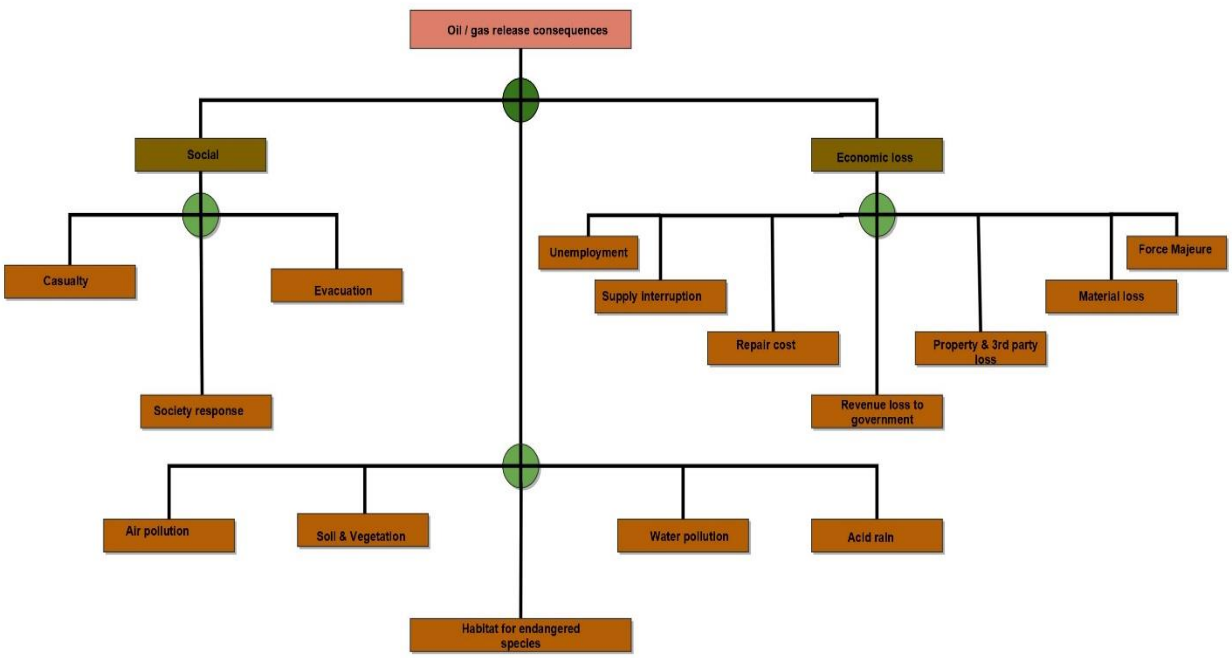


Figure 33: Hierarchical framework for consequences of output events in the Niger delta region of Nigeria.

- Social Consequence

This is given the highest attention and relates to social criteria involving injuries to humans, human cost, evacuation and social response etc. Several losses of life are recorded in Nigeria to the acts of vandalism, as the casualty includes, the militants, youths, security agents, company personnel etc. as observed in Rumuekpe, Bele, Obele-ibaa, Ogbakiri all in the communities of Rivers state (Wilson, 2004). Such life loss comes in two forms:

a. Either during gun battle between the host community youths, militants and the state security agents while siphoning the crude oil from oil pipelines and well heads or

b. During fire outbreaks, which occurs during the siphoning of the crude oil or during the local refining of the crude oil by the oil criminals. In Nigeria, the village opulation is mostly comprised of the poor, making them very vulnerable to these fire outbreaks. Among these, the women are the most hit followed by the children (Whitaker and agencies, 2006).

- Environmental consequence

These are the actual environmental damages which constitute biological effects and impacts on the ecosystem. In the Niger delta region, these include, the air pollution, the water pollution from toxins from petroleum products like mercury, chromium etc. which cause health problems to human beings when consumed and the loss of the sources of their drinking water, the expanse of vegetation destroyed with the corresponding loss of endangered species, the acid rain due to gaseous emissions in the air.

- Economic Consequences

These not only relates to operational losses incurred during pipeline failure but also losses incurred by the government as it regards the revenue that are supposed to be gained by the government but have been lost due to pipeline incident and the emergency response in the case of severe accident. The Nigerian National Petroleum Cooperation (NNPC) declared the loss of #2.1tn equivalent of $7bn from January 2016 till date to the activities of militancy groups and oil pipeline vandals in the Niger Delta region (NNPC report, 2016). Some other form of economic losses come inform of reimbursement to customers for production interruption, revenue loss from supply interruption, expenses required for labor, equipment etc., compensation for damage caused to the third party etc. Etekpe and Okolo (2010), highlighted the various socio-economic consequences pipeline vandalism poses to the people of Niger delta. The incessant declaration of force majeure by oil multinationals operating in the region due to the acts of vandalism has resulted in the reduction of Nigeria’s production and export capacity leading to a fall in oil export revenue. This on the other hand increases the level of unemployment in the country due to under-production capacity. The highest level of this, is the threat from some of these oil multinationals to move their production to another country (Wilson, 2004).

5 Discussion and Conclusion

5.1 Discussion

The objective of this research has been to establish an effective way to monitor/manage the integrity of oil and gas pipelines since the lifecycle perspective cannot fully account for oil bunkering, pipeline vandalization that is often experienced in developing nations. The first approach towards achieving this objective was to identify the different leverage points where necessary systemic changes needed to be effected. After studying the different leverage points, four leverage points were adopted for systemic change. These are

- Pipeline design stage
- Pipeline operation and maintenance stage
- Pipeline monitoring and inspection
- The mindset or paradigm out of which the pipeline arises.

The identification of these leverage points for systemic change gave room for answering the different research questions which are as stated below:

RQ 1. What are the major systemic risks to pipelines?

These are the different integrity threats that an operating pipeline faces over its entire lifecycle. They fall under three categories:

- Time dependent threats

These are threats that grow over time. They include:

(1) Corrosion (internal and external) (2) Creep and crack mechanism

- Resident threats

These are threats that do not grow over time but act when influenced by another condition or failure mechanism. They include:

(1) Mechanical damage from construction/fabrication (2) Material and construction defects like pipe seam, pipe body and joint welds (3) Maintenance deficiencies (4) Third party activity like sabotage

- Time -independent threats

These threats are not influenced by time. They include:
(1) Human error (2) Incorrect operation (3) Device failure and malfunction (4) Excavation damage (5) Earth movements such as earthquakes, landslides or telluric currents (6) Outside forces or weather related threats like high winds, rough seas or cold/ hot temperatures.
It was established that Pipeline sabotage is the most predominant threat in developing countries most especially, the Niger delta region of Nigeria where high poverty and negligence from the government and the oil companies operating in the region are the main contributive factors to sabotage that is often practiced in the region. Corrosion was also discovered to be the most prevalent threat across US and Europe and accounts for the major pipeline losses that have been incurred in those areas.

RQ 2. What methods are appropriate to address the integrity of pipelines during the delivery phase of the oil and gas sector?

Various methods were adopted in this research to address the integrity of oil and gas pipelines during the delivery phase. Such methods include:

- Failure mode and event analysis (FMEA)

This was adopted to identify and prioritize the root causes of these pipeline integrity threats and the consequences that will result from the damaged pipeline in case a failure occurs. This was achieved by carrying out a bow-tie analysis of the oil and gas pipelines in the Niger delta region. The bow-tie analysis consists of two basic parts:
(1) Fault tree part: This was used to identify the main factors and sub factors that contribute to pipeline failure in the Niger delta region. This led to the development of the event tree of possible failure modes of pipelines.
(2) Event tree part: This was used to analyze the outcome events of oil and gas release from failed pipelines in Niger delta region of Nigeria. The analysis resulted in three types of consequences namely: social, environmental and economic consequences.

- Integrity Performance Indicators

The need for the pipeline integrity to remain at a certain level or threshold was emphasized in this work. This is because exceeding certain level or going below the threshold results in catastrophic consequences. Therefore, pipeline integrity should not exceed certain level and as well should not fall below the threshold level. For this to be ensured there is the need for continues monitor of the integrity level. This is achieved using the pipeline integrity performance indicators. The risk based integrity indicators were developed in this research to monitor the integrity level of pipelines so as not to exceed or fall below certain level. This would help in averting the consequences that results from the pipeline failure by ensuring that a good integrity level is maintained.

- Condition based maintenance methods

Different techniques were adopted to monitor the condition of pipelines. These are of two types: (1) Prognostics techniques: These are the different measures adopted to predict fault/failures before they occur. They are the different inspection and monitoring techniques given to pipelines to ensure its integrity. Such inspection or monitor are done using smart pigs. Smart pigs are used to detect loss of metal and deformation in pipeline. They come in three dimensions: (a) metal/thickness loss which monitors the thickness of pipelines (b) Crack detection which monitors the pipeline for cracks (c) Geometry tool which gather information about the shape of pipeline or its geometry. It also monitors the external surface of pipelines and dents as well.

(2) Diagnostics techniques: These are methods used to detect, isolate and identify faults or failures in pipeline. They comprise the different leak detection methods discussed in this work from the simplest method of using trained dogs to detect bleaks to the advanced method of using satellite. These leak detection methods were categorized in three groups, namely:
(a)Hard ware based method: These utilize hard ware tools for the detection and localization of leaks in pipes (b) Biological method which is a traditional method of leak detection where experienced personnel or trained dogs walk along the pipeline looking for patterns like odour emanating from the pipeline, listening to noise from the leaking holes in pipelines. (c) Software based method which utilizes computer software programs for leak detection in pipelines.

- Integrated operations

This method is utilized to monitor oil and gas pipelines from remote locations. It allows for tighter integration of personnel that are involved as well as operators and service companies working together to plan, operate and maintain the oil and gas pipeline. This is made possible by modern information and communication technology and high band width fiber optics network for real time data sharing between remote locations.

RQ 3. What indicators can support risk framework used to secure pipeline delivery system?
Risk-based leading and lagging indicators were developed for the different selected leverage point to monitor the integrity level of oil and gas pipelines so as not to exceed a certain limit or fall below the threshold level. These indicators are as presented in the following tables 5,6,7,8.

Table 5: Design Stage Integrity Performance Indicators

<table>
<tr><th colspan="4">Design stage</th></tr>
<tr><th colspan="2">Design Effectiveness</th><th colspan="2">Compliance to statutory requirements</th></tr>
<tr><th>Lagging Indicators</th><th>Leading Indicators</th><th>Lagging</th><th>Lagging</th></tr>
<tr><td rowspan="2">*No. of incidents associated with changing threats and failure modes not considered during pipeline design</td><td>Allowable size of population along pipeline route.</td><td rowspan="6">*No. of incidents where errors in pipeline design are identified as contributory cause</td><td>No. of deviations from applicable codes, standards and regulations governing pipelines in a country</td></tr>
<tr><td>Environmental and external loads on pipeline</td><td>No. of post-startup modifications required by operations</td></tr>
<tr><td rowspan="2">*No of incidents due to improper route selection

* Production loses due to route selection in difficult terrain</td><td>Percentage cost saving due to shorter route selection</td><td rowspan="4">% critical equipment/systems fully in compliance with current design codes</td></tr>
<tr><td>Time taken to get to critical location</td></tr>
<tr><td rowspan="2">* No of incidents linked to failure of MOC</td><td>% pipeline section changes suitably risk assessed and approved before installation.</td></tr>
<tr><td>Average time taken to fully implement a change once approved</td></tr>
</table>

Table 6: Inspection/ Maintenance Integrity Performance Indicators

Inspection/Maintenance					
Inspection strategy		Inspection effectiveness		Compliance to statutory rules	
Lagging indicators	Leading indicators	Lagging indicators	Leading Indicators	Lagging indicators	
*No. of incidents due to incorrect maintenance / inspection strategy	The standard of inspection and maintenance strategy	*No. of incidents due to lack of inspection and maintenance	% availability of inspection and maintenance equipment	*No of incidents due to non-compliance with rules and regulations	Performance of inspection and maintenance by qualified and certified personnel
*No of incidents due to involvement of unqualified 3rd party in inspection and maintenance	The procedure for inspection and maintenance of each section of the oil and gas pipeline	*No. of incidents due to overrun of inspection	Consistency with written procedures and checklist	*No of incidents due to avoidance of rectification recommendation	Proper documentation of inspection information, activities and data
*No of incidents	Involvement of third party inspection body	*No of incidents due to insufficiency in inspection and testing	No. of inspections and maintenance duly completed on schedule	*No of incidents due to operation of inspection and maintenance equipment without complying to the rules as stipulated by equipment manual	Systematic appraisal to determine compliance with applicable standards
	Written scheme for periodic		Strategy for uncompleted inspection activity		

due to incorrect application of inspection and maintenance strategy	inspection and testing		Timely performance of inspection and maintenance		
		*No. of incidents due to unavailability of pipeline maintenance equipment	Leak sensitivity of pipeline inspection tool		
			Location estimation capability of inspection equipment		
		*Frequency of leak alarm generated by pipeline leak inspection equipment during leak-free operations.			
		*No. of incidents due to improper location of leaks in pipelines			

Table 7: Operational Integrity Performance Indicators

Operational Performance Indicator					
State of the pipeline		State of the Operating personnel			
Lagging Indicators	Leading Indicators	Staff Competency		Effort Motivation	
		Lagging Indicators	Leading Indicators	Lagging Indicators	Leading Indicators
*No. of incidents linked to failure of instrumentation or alarms	% tests of alarms/trips completed on schedule	*No. of incidents linked to poor operation skills	Minimum qualification before recruitment	Number of incidents linked to poorly motivated operators	Percentage of personnel who are promoted
*No. of operational errors due to incorrect/unclear procedures	% of procedures, plans reviewed and updated	*No of incidents linked to poor communication between the pipeline operating personnel	Quality of on -the- job training received by operating personnel		Individual reward system available for operating personnel
*No. of emergency response elements that are not fully functional when activated in real emergency	% of emergency shutdown (ESD) valves and process trips tested using a schedule defined in a relevant standard or the pipeline safety case	*No. of incidents linked to insufficiently trained personnel	Level of quality improvement programs given to pipeline operating personnel		Average salary of pipeline operating companies Job security
*No. of incidents where errors in permit to work process (PTW) are identified as contributory cause		No. of equipment damage linked to insufficient understanding, knowledge or experience of correct actions	% training courses matching pipeline requirements		
	% PTWs sampled where all				

	hazards were identified and all suitable controls were specified		Average period required to become fully competent after appointment to a new position		
	% PTWs where all controls listed were fully in place and functional at worksite		% of personnel sampled who have participated in emergency exercise in the past X months		
			Proportion of professionals in the operating company		
			Value added per professional		

Table 8: Paradigm Integrity Performance Indicators

Paradigm Indicators			
Corporate societal responsibility		Environmental Aspects	
Lagging Indicators	Leading Indicators	Lagging Indicators	Leading Indicators
*No. of pipeline incidents linked to youth unemployment	% unemployed youths in the pipeline host community	*No of incidents linked to poorly risk-assessed pipeline section	Vulnerability and risk assessment
	% employment offered by the pipeline operating company to the local community	*No. of fatality recorded due to poorly estimated impact during an incidence	Estimation of impact during a period of exposure
		*No. of incidents linked to lack of risk management training and education	Risk management training and education
		*No. of incidents linked to poor communication and awareness of environmental implications of oil spills and gaseous emissions	Public information and community participation
*No. of pipeline incidents linked to high level of poverty within the locality of pipeline route	Poverty level in the immediate locality of the pipeline route		
*No. of incidents linked to poor infrastructural development of the pipeline host community	Level of infrastructural development provided by operating company and the government to the host community	*No. of incidents caused by the high level of environmental degradation due to the activities of the oil and gas pipeline operating company.	Level of environmental degradation caused by the activities of the oil and gas pipeline operating company
	Community development activities performed by the operating company and the government	*No of incidents that are linked to incorrect operation of pipeline due to poor understanding of the environmental impact	Quality of environmental training and communication to operating staff

Paradigm Indicators			
Corporate societal responsibility		Environmental aspects	
Lagging Indicators	Leading Indicators	Lagging Indicators	Leading Indicators
*No. of incidents linked to breaches of agreement between the operating company and the community or between the host community and the government	Agreement breaches between the pipeline operating company and the host community	*The no. of incidents whose causes were not able to be detected due to poor environmental auditing and performance	The quality of environmental auditing and performance
*No. of incidents linked to improper or misunderstanding between the government and the host community concerning the sharing formula	Sharing formula for proceeds from oil revenue between the government and the host community	*No of incidents linked to poor or improper hazard monitoring and forecasting	Hazard monitoring and forecasting

5.1.1 Section Summary

From the failure probabilities developed across four different states of the Niger delta region of Nigeria as presented in table 4, Akwa-ibom state has the least failure probability for sabotage but with the highest number of incidents due to corrosion (internal and external put together). This is attributed to the fact that oil and gas operation in this state is basically offshore which makes it difficult for vandals to get easy access to the facilities.

Rivers state has the highest number of sabotage probability followed by Delta state since the operations in these states are done on onshore locations which gives vandals easy access to the pipelines. Construction defect probabilities are same across the states because it is assumed that the construction is done by the company involved and has nothing to do with the state where the pipeline is located.

Going by the above findings, in order to ensure that the integrity of oil and gas pipeline are ensured in these four states and that the integrity level of these pipelines do not exceed a certain limit or fall below the given threshold, the following are recommended:

- The design stage integrity performance indicators are recommended for all the four states in the Niger delta region of Nigeria.
- The operational integrity performance indicators and inspection/maintenance integrity performance indicators are recommended for Akwa-ibom state.
- The paradigm integrity performance indicators are recommended for Rivers state, Delta state and Bayelsa state together with the operational integrity performance indicators and inspection/maintenance integrity performance indicators.

5.2 Conclusion

In this thesis, a review of the life cycle view of asset (pipeline) management has been presented. To gain a good background of oil and gas pipeline failure modes, integrity threats with their different control measures were presented as well.

Subsequently, in a bid to adopt an efficient method for managing the integrity of oil and gas pipeline (since the lifecycle perspective cannot fully account for pipeline sabotage and vandalism often experiences in developing nations like Nigeria), four leverage points in which to effect systemic changes were explored and one of such leverage points incorporated the stakeholder view to account for oil and gas pipeline sabotage and vandalism.

Failure mode and event analysis of oil and gas pipelines in four Niger delta states of Nigeria was carried out using the bow-tie analysis risk framework which led to the development of fault tree and event tree.

Finally, from the result of the failure analysis carried out on oil and gas pipelines in the Niger delta region, sabotage was established as the major threat to oil and gas pipeline in that region. Four leverage points in which to effect systemic change were studied in a bid to efficiently manage this problem. Three of these leverage points are basically on the system (material domain) while the fourth leverage point is external to the system (relational domain).

From findings, system (material) changes do little to change the systemic condition but moving from (system) domain to external (stakeholder) or relational domain is equivalent to expanding the boundaries of the system to include more opportunities for intervention. Therefore, in finding an efficient way to fully account for oil and gas pipeline vandalization and sabotage that is often experienced in developing countries, the lifecycle perspective which considers only the system domain cannot fully account for sabotage, but extending the boundary to consider the stakeholders (relational domain) of the system gives more room or opportunities for intervention on the oil and gas pipeline system, thus making the fourth leverage point (paradigm), the highest leverage point for systemic change.

The different interventions needed in this leverage point as well as the other leverage points were discussed in this work and the performance indicators were developed as well to ensure that the integrity of oil and gas pipelines in this region does not exceed a certain level or fall below the given threshold.

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