Inspection and maintenance of oil & gas pipelines: a review of policies

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Inspection and maintenance of oil & gas pipelines: A review of policies

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Abstract

Oil and gas (O&G) pipelines are expensive assets that cross through both ecologically sensitive and densely populated urban areas. The pipeline failure may have potentially significant consequences for both natural and human environments. Inspection and maintenance processes of O&G pipelines should be governed by efficient policies in order to maintain their integrity. The objective of this paper is to conduct a state-of-the-art review of maintenance policies of O&G pipelines to investigate their advantages, limitations, and associated implementation issues. Maintenance policies can be categorized into corrective, preventive, predictive, and proactive. Corrective maintenance policies (1940s) were based on a "repair when broke" philosophy. Economic considerations shifted practice towards preventive maintenance (1970s to 1990s); later with improved inspection techniques and environmental regulations, predictive and proactive or risk-based maintenance (RBM) policies were developed. This review explicates different methodologies for RBM and related issues, e.g., uncertainties and variability, conservative assumptions, etc. Uncertainties associated with investigation and prediction of defects have been more frequently reported in the literature so far. Moreover, existing studies primarily focused on reducing the likelihood and cost of failure, whereas consideration of environmental factors in overall risk has been a relatively less addressed issue.

Keywords: Inspection and maintenance; oil & gas pipelines; maintenance policies; time-based maintenance; condition based maintenance; risk-based maintenance.

Abbreviations

Oil & Gas	O&G
National Energy Board Canada	NEB
Pipeline Integrity	PI
American society of mechanical engineers	ASME
American Petroleum Institute	API
Corrective maintenance	CM
Preventive maintenance	PM
Time-based preventive maintenance	TBPM
Condition based maintenance	CBM
Condition based inspection and maintenance	CBIM
Risk based inspection	RBI
Risk-based maintenance	RBM
Risk-based inspection and maintenance	RBIM
Inspection and maintenance	I&M

1 Introduction

Oil and gas (O&G) pipelines are expensive assets that cross through both ecologically sensitive and densely populated urban areas. If pipelines are not well maintained, they may fail with potentially significant consequences that could have severe, long-term and irreversible impacts on both natural and human environments. The United States Department of Transportation reported more than 10,000 failures in O&G networks across the country which caused losses around six billion US dollars in the form of property damage, production losses, environmental impact, and human casualties. The 2013 American Infrastructure Score Card described the condition of O&G pipelines in America as 'poor' (Parvizsedghy, Senouci, Zayed, Mirahadi, & El-Abbasy, 2014). Excessive infrastructure failures can lead to poor performance, and, consequently production loss and high economic impact (Biondini & Frangopol, 2015; Castro & Sanjuán, 2008). Therefore, to avoid failure and to improve the reliability of infrastructure, planned maintenance is the integral activity (Hongzhou Wang, 2002).

An effective maintenance policy outlines the allocation of resources and time for corrective or preventive actions based on possible threats and incidents. O&G pipeline integrity managers are facing challenges in developing and implementing cost-effective and proactive maintenance policies selection criterion and solution models (Li, Sun, Ma, & Mathew, 2011). Effective maintenance policies became more significant due to the increasing demand for system availability, lack of human resources, financial constraints, climate change, stringent environmental regulations, and system ageing (Kabir, Sadiq, & Tesfamariam, 2013).

Although a number of articles related to the maintenance of O&G pipelines have been published, few have specifically addressed the subject of I&M policies. The other literature mostly discussed either techniques and methods for I&M of the physical condition of pipelines or the prediction models of corrosion defects. Moreover, to the best of our knowledge, there is no review article published on this topic covering state-of-the-art maintenance policies in the recent past. Several classification criterion are developed for a better understanding of existing concepts, methodologies, and techniques related to the topic.

The scope of the review primarily focuses on inspection and maintenance (I&M) policies of O&G pipelines reported in peer-reviewed literature. The main objectives of the review are to i) outline, in support of the subject, a general review of maintenance policies for industrial and infrastructure assets to evaluate their applicability for oil and gas pipelines; ii) conduct a state-of-the-art review of maintenance policies of O&G pipelines to investigate their practicality, advantages, and limitations; and iii) identify uncertainties affecting the decision making process for maintenance of O&G pipelines and highlight less addressed issues to improve the existing practices. To achieve this objective, the following topics are discussed in the review:

- a comprehensive review has been conducted to investigate the evolutionary process of maintenance policies for different types of infrastructure including bridges, power plants, offshore platforms, underground constructions, pipelines, and ocean structures (D. M. Frangopol, Saydam, & Kim, 2012);
- pipelines are considered as infrastructure systems, whereas individual segments and auxiliary equipment such as valves, filters are treated as industrial assets; therefore, a brief review of maintenance policies of industrial assets has also been carried out;
- the policies suitable for Oil and & Gas pipelines are discussed in detail, and a brief overview of pipeline inspection and monitoring methods has also been conducted.

The remainder of the article begins with section 2, providing a brief overview of pipeline systems, pipeline integrity management and inspection methods, and the historical evolution of maintenance policies. Section 3 presents a detailed review of the maintenance policies for O&G pipelines and the factors influencing the effectiveness of these policies. Finally, Section 4 summarizes the conclusions of the review.

2 Background

2.1 Pipeline Systems

The National Energy Board of Canada (NEB) Act, defines an oil and gas pipeline system as "*a line that is used or to be used for the transmission of oil, gas, alone or with other commodities and includes all branches, extensions, tanks, reservoirs, storage facilities, pumps, racks,* *compressors, loading facilities, interstation systems of communication by telephone, telegraph or radio and real and personal property, or immovable and movable, and works connected to them, but does not include a sewer or water pipeline that is used or proposed to be used solely for municipal purposes*" (Board, 2005). Figure 1, shows pipeline types in a crude oil pipeline system, which consist of gathering lines and main transmission lines, whereas a gas pipeline system has three types of pipelines: gathering lines, transmission lines, and distribution lines. Sizes of gathering lines range from 2 to 12 inches, and the sizes of a transmission line are mostly 8 inches and higher (Miesner & Leffler, 2006). Certainly, the consequences of failure and associated costs of repair depend on both the location and size of the pipe, i.e., gathering lines vs. transmission lines.

Regarding maintenance, the structure of pipeline system can be divided into repairable and non-repairable units (Ahmad & Kamaruddin, 2012). Crow (1975) defined a repairable structure as, ‘‘*one that can be repaired to recover its functions after each failure rather than be discarded”.* Based on their operational characteristics, the pipelines have been classified as high-pressure and low-pressure pipelines, and as rigid or flexible based on their stiffness properties. Gas pipelines are single phase flow pipelines; whereas oil pipelines are three phase flow pipelines, i.e., oil, water vapours, and gases (Taitel, Barnea, & Brill, 1995). Oil pipelines are more vulnerable to failure due to internal corrosion as compared to gas pipelines. The failure of gas pipelines has high consequences due to a potential of rapid spread in the environment, whereas failure of oil pipelines has long lasting impacts on the surrounding environment and groundwater (Prasanta Kumar Dey, Ogunlana, & Naksuksakul, 2004).

At the design stage, safety and reliability are important factors in consideration. The traditional design followed a deterministic stress based methodology. High-pressure pipelines, temperature, pipe-bending stresses by the lateral load, internal corrosion and erosion are important factors to be considered in traditional design methodology (Zhou, Rothwell, Nessim, & Zhou, 2009). For low-pressure pipelines, external factors and soil properties, such as soil corrosivity, moisture, and soil-pipe interaction, are significant factors. Other factors at the design stage that can influence the integrity of pipeline and cost are; installation, pipe rigidity, pipe stiffness, external pressure, earth load, live load, type of construction, bedding factor and safety factor

(Kishawy & Gabbar, 2010). However, the optimal design is the balance between safety and economy (Psarrpopulos, Antoniou, & Tsompanakis, 2014)

Apart from static design approach, reliability based design approach is adopted in oil and gas pipeline design. This approach builds a strong relationship between design, operation, and maintenance (Zhou et al., 2009), and has many significant advantages over traditional method, for instance, it directly addresses the actual mechanism of failure and integrates design with operation and maintenance. It maintains the consistent level of safety, provides an optimal allocation of resources, and offers an assessment of technologies used in pipeline operations and maintenance (Zhou et al., 2009). Reliability based design is also recommended in the pipeline industrial standards CSAZ662 and ASME B31.8S. The readers may refer to significant work on reliability-based design reported by Nassim and Zhou (2009).

2.2 Pipeline Integrity Management

The US Department of Transportation Pipeline and Hazardous Materials Safety Administration defines Pipeline Integrity (PI) as *"[t]he ability of a pipeline to operate safely and to withstand the stresses imposed during Operations"* (Transportation Pipeline & Administration, 2003). The primary objectives of an asset integrity program are; asset safety, uninterrupted and smooth operations, efficient production process, the effective utilization of human resource, and asset life improvement (Adebayo & Dada, 2008; Chang, Chang, Shu, & Lin, 2005; Dawotola, Van Gelder, & Vrijling, 2009; Rahim, Refsdal, & Kenett, 2010; Simonoff, Restrepo, & Zimmerman, 2010; Yuhua & Datao, 2005). These objectives can be achieved through: i) a reliable design, ii)a planned inspection, monitoring and repair program during operations, iii), implementing risk mitigation and performance optimization, and iv) maximizing life and availability of assets (*Pipeline Safety Improvement Act of 2002-Operator qualification (OQ) protocols,U.S. Department of Transportation's Office of Pipeline Safety (OPS)*, 2002).

The integrity management systems for pipelines can broadly categorize into i) technical systems integrity and ii) management system integrity. Technical standards and procedures are guidelines to maintain the technical integrity while management integrity can be achieved by following appropriate management manuals and documentation (T. Wang, Feng, Zheng, Sun, &

Chang, 2011). Oil & Gas pipeline industry is using industrial technical and management standards to maintain the integrity of pipelines as per type of assets and regulatory authorities' requirements. Most common industrial standards are: American standards, API 1160 (Liquid Pipeline Integrity Management), ASME B31.8S (System Integrity for Gas Pipelines) and API 1163 (In-Line Inspection System Qualification); Canadian Standards, CSAZ662 (Oil and Gas pipeline systems); British standards, BS PD8010 Part 1 (Steel Pipelines on Land) and part 2 (Subsea Pipelines); and European standards, BS EN 14161 (Petroleum and natural gas industries-Pipeline transportation systems), BS EN 1594 (Gas Supply Systems).

Good design, improved materials, inspection, and maintenance techniques have significant impacts on O&G pipeline integrity records (Cosham, Hopkins, & Macdonald, 2007). The technical integrity of a pipeline can be compromised due to material and construction defects, damages from a third party construction, operational mistakes, accidents, device failures and malfunctioning, and environmental and climatic factors (i.e., corrosion, creep, cracking, weather and temperature change, earthquakes, landslides and floods) (Adebayo & Dada, 2008; Dawotola et al., 2009; Psarrpopulos et al., 2014; Simonoff et al., 2010; Yuhua & Datao, 2005). The main components of a pipeline integrity management are (Kishawy & Gabbar, 2010):

- Failure identification process of pipelines in high consequence areas;
- Assessment baseline plan;
- An integrated analysis of defect information and failure consequences of the pipeline integrity ;
- criteria for repair actions based on information analysis during assessment plan;
- A continuous improvement plan of pipeline integrity by assessment and evaluation;
- Preventive and mitigation measures to protect the high consequence areas;
- Program's effectiveness measurement methodology;
- A process of information analysis and the review of integrity assessment results;
- A process of management of change; and
- A process of record keeping and documentation control.

Pipeline integrity can be enhanced by lessons learned from past accidents, inspection, testing, analysis, and proper long-term maintenance of a system (Rahim et al., 2010).

2.3 Pipeline Inspection

Condition evaluation and probability of failure for pipelines are the most important factors for effective maintenance decision-making. Traditional deterministic/ mechanistic approach based on standards and codes such as ASME B31G and modified B31G; and ii) the probabilistic/ statistical approach based on the stochastic character of structural and environmental factors are used to assess the probability of pipeline failure: (Sahraoui, Khelif, & Chateauneuf, 2013). The deterministic approach is a process to assess the condition of pipelines by getting data from inspection tools, whereas the probabilistic approach uses the data to predict the future probability of failures. ASME B31G provides industrial guidelines (ASME, 2009) of safe working pressures based on the pipeline dimensional parameters obtained through inspection (M. Singh & Markeset, 2014a). The DNV-RP-F101 recommends the probabilistic assessment approach for the assessment of corroded pipelines subject to internal pressure and internal pressure combined with longitudinal compressive stresses (Bjørnøy et al., 1999; DNV, 2015). Routine and planned inspections play a significant role in safe operations and availability of equipment (F. Khan, Sadiq, & Haddara, 2004).

Pipelines are inspected by internal or intrusive inspection and external or non-intrusive inspection processes. The most common processes for pipeline inspections are pigging, hydro-testing, and external and internal corrosion assessments (Cosham et al., 2007). Pigging techniques are used for cleaning and internal condition monitoring/ inspection for longer length pipes. The pigging process was established in the 1960s. The pig is a cylindrical shaped electronic device with condition monitoring capabilities. Pigs equipped with condition monitoring systems are also known as smart pigs or inline inspection tools. Smart Pigs are the most commonly used tool in the pipeline industry (Kishawy & Gabbar, 2010; Klechka, 2002; H. Liu, 2003; Manian & Hodgdon, 2005; Rankin, 2004). Further types of smart pigs are the magnetic flux leakage and the ultrasonic pigs. The basic components of a smart inspection PIG (magnetic flux leakage type) are shown in Figure 2. It consists of drive packed which moves PIG in the pipeline, flux loop generates the magnetic flux and recorder package, equipped with sensors, records the variation in flux, location.

These pigs have been used to find metal loss, cracks, pits shape, length and maximum pit depth, and wall thickness due to corrosion and erosion. The crack detection pigs are the most recent development of the inspection methods. The ultrasonic crack detectors, transverse magnetic flux leakage, and elastic wave pigs are used to detect circumferential and longitudinal cracks (Kishawy & Gabbar, 2010). Industrial standard API 1163 provides in-line inspection system qualification.

In addition to pigging, the condition of the pipeline can be assessed from operational parameters such as pressure, flow rate, and physical dimensions. Geometry tools have been used to determine the physical shape and geometry conditions of the pipelines, e.g., caliper tools and pipe deformation tools. Mapping tools, integrated with a global positioning system, are used to locate valves, equipment positions and for mapping of pipelines. Low-frequency long-range guided wave inspection technique is used to map corrosion and erosion in pipes. Hydrostatic testing is a process to pressurize the pipeline above the normal operating pressure, which detect manufacturing and metal loss defects; this test is carried out at the manufacturing stage and the completion stage before operations. Axial flaws such as stress corrosion cracking, longitudinal seam cracking, selective seam corrosion, long narrow axial corrosion, and hydrostatic testing better detects axial gouge than by pigging (Kishawy & Gabbar, 2010).

A pipeline system is a combination of pipelines, valves, and connected rotary auxiliaries such as compressors, pumps, and their prime movers. The vibration induced by the rotary auxiliaries also affects the pipeline integrity. Vibration monitoring is the most popular technique to monitor the condition of the rotary auxiliaries (Ahmad & Kamaruddin, 2012; Al-Najjar, 1997; Carnero, 2005; Hagene, Haugholt, Tørring, & Vartdal, 2005; Higgs et al., 2004). Other techniques for condition monitoring of rotary auxiliaries are sound or acoustic monitoring (Ahmad & Kamaruddin, 2012), oil analysis or lubricant monitoring, electrical temperature and physical condition monitoring (Ahmad & Kamaruddin, 2012; Newell, 1999).

Technological advancements have significantly improved the inspection processes; however, different types of uncertainties are involved in an inspection process, such as the probability of miss detection of small holes, wrong assessment of defect existence and size, etc. The inspection process of selected small segments of a pipeline with such deficiencies is known as imperfect inspection; it may lead to costly maintenance or poor safety. A detailed discussion of uncertainties is presented in the following sections. For more details about inspection methods of pipelines interested readers may refer to Hagene et al. (2005) and Kishawy & Gabbar (2010).

Despite deterministic/mechanistic approach to estimate the pipeline condition, the probabilistic/statistical approach is also discussed in the literature based on the models trained on data obtained through deterministic methods. The pipeline condition data is either obtained from the field or from the laboratory experimental work. The prediction accuracy depends on the accuracy of ILI tool and data quality obtained from the field. The influencing factors on corrosion growth rate, such as soil properties, temperature, sulfate ion, CO_2 partial pressure, chloride ion concentration, wall shear stress, water content, corrosiveness, pH, concentration and flowrate of carrying fluids are heterogeneous in nature. To address these issues, different probabilistic models are presented in the literature which is summarized in Table 1.

2.4 Evolution of Maintenance Policies

Maintenance can be described as "*the set of activities or tasks used to restore an item to a state in which it can perform its designated functions*"(Ahmad & Kamaruddin, 2012). The objectives of a maintenance policy are to: effectively plan maintenance activities, maximize the availability and efficiency of equipment , reduce failure, control deterioration, ensure safe and correct operation, and minimize the cost for keeping a unit operational within an acceptable level of safety (Arunraj & Maiti, 2007; Dhillon, 2002; S. O. Duffuaa, Raouf, & Campbell, 1999; Tan, Li, Wu, Zheng, & He, 2011). Maintenance can be broadly categorized as corrective maintenance (CM) and preventive maintenance (PM) (S. Duffuaa, Ben-Daya, Al-Sultan, & Andijani, 2001). CM is performed at the time of system failure; while PM is a systematic approach to the inspection, detection and prevention of the anticipated failures to keep the system in a specific condition (Wang, 2002).

According to the traditional approach, the failure behaviours of equipment are somehow predictable and can be described with the help of the famous bathtub curve showed in Figure 3 (Ahmad & Kamaruddin, 2012). The bathtub curve divides failure trends into three phases of operations: burn-in, useful life and wear-out phase (Ebeling, 2004). The burn-in and wear-out phases are more critical for the failure of the unit and may have a higher rate of maintenance than useful life phase. However, the actual behaviour of equipment or infrastructures is much more complex than simply defined by bathtub curve. The maintenance decisions are taken to overcome possible threats of failure due to metal loss, external damages, manufacturing errors, human operational mistakes and asset's age within economic constraints (Ahmad & Kamaruddin, 2012; Dawotola, Trafalis, Mustaffa, Van Gelder, & Vrijling, 2012; Prasanta Kumar Dey et al., 2004; Prasanta Kumar Dey, 2003, 2004; M. Singh & Markeset, 2009; Tan et al., 2011). Implementation of maintenance policies is a multi-criteria decision-making problem which depends on several factors, e.g., type of asset, asset condition, redundancy and reliability of a system, availability of maintenance resources (both human and logistic), reliability of maintenance, downtime cost, maintenance operational cost, response time, organizational structure, environmental and socio-economic factors (Arunraj & Maiti, 2010; Stenström, Norrbin, Parida, & Kumar, 2015; Sun, Fidge, & Ma, 2014).

Maintenance policies have evolved over time, and can be classified based on the time of application and the geographic location of an asset for single or multi-units as (Barnard, 2006; Moubray & Lanthier, 1991):

- Corrective maintenance,
- Preventive maintenance,
- Predictive maintenance,
- Proactive maintenance.

Figure 4 describes different phases of evolution of maintenance policies. The first phase started in the 1940's, when policy makers relied on a corrective maintenance philosophy, "*Fix it when broke.*" The policy can also be recognised as a reactive policy because repair or replacement actions were performed only at complete equipment or unit failure (Barnard, 2006; Tan et al., 2011). In the second phase, during the 1970's, policies were primarily based on the preventive maintenance approach. In this generation of maintenance policies, the objective was focused on preventive actions to reduce the rate of failure and the consequences of failure (e.g., long shutdown time, production loss and high maintenance cost) (Usher, Kamal, & Syed, 1998). In contrast corrective maintenance (CM), the maintenance activities were performed before the failure of the equipment or unit (Gertsbakh, 1977; Löfsten, 1999). The philosophy of second phase policy is based on preventive overhauls, i.e., repair of equipment/unit at fixed and scheduled intervals depending upon the age or time in service or limiting the number of failures or repairs.

The further extensions of the PM policies are predictive and proactive maintenance policies, which aim to reduce the cost and enhance the reliability. These more strategic policies such as condition-based maintenance, reliability centered maintenance, computer-aided maintenance management, and information systems have been adopted most frequently since 1980's. However, the initial work was started in 1960's (Moan, 2005). These policies can be considered as the 3rd phase of maintenance policies. The most of the literature related to the third phase spanned over two decades from 1980 to 2000. In these policies, maintenance decisions were made based on equipment/ unit's health condition. The equipment/unit health condition was monitored at regular intervals or a continuous basis. Preventive maintenance was carried out once the health of the unit reached a predefined threshold level. The fourth generation policy of 21st century has been the most adaptive approach in recent past where the maintenance policies are characterized by risk-based inspection and maintenance (RBIM). These policies are also known as proactive policies (Arunraj & Maiti, 2007). The main objective of these policies is to avoid failure and to mitigate the root causes before the failure happens with emphasis on high consequences causes, areas and more vulnerable parts of an infrastructure. The basic difference between the predictive maintenance and the proactive maintenance policies is that decisions in former mainly focus on the condition of equipment whereas later considers the risk of failure. The decision-making criterion are elaborated in sections 3.3 and 3.4. The readers may also refer to the review presented by D. M. Frangopol et al.(2012) for recently published articles about maintenance, management, lifecycle design, and performance of structures and infrastructures.

3 Inspection and Maintenance Policies for O&G Pipelines

In general, O&G pipelines are considered to be one of the safest modes of transporting petroleum products (Brito, Almeida, & Mota, 2010; Papadakis, 2000) due to their low accident frequency (Shahriar, Sadiq, & Tesfamariam, 2012). However, with aging, these assets deteriorate and need repairs. An efficient maintenance decision includes two important considerations: selection of the right pipe at the right time, and selection of an optimal maintenance strategy implemented using a cost efficient technology (Li, Ma, Sun, & Mathew, 2014). The causes of failure of a pipeline can be classified into two broad categories, i.e., external and internal. The external causes of failures include first, second and third party accidents, device failure and malfunctioning, natural disasters, extreme weather temperature variations, and improper installation and repairs (Guo, Song, Ghalambor, & Chacko, 2005; Kishawy & Gabbar, 2010). The internal causes of failure are corrosion, erosion, material defects, weld crack, fatigue, and vibrations (Guo et al., 2005). Mechanical damage and corrosion are the most common causes of failure of O&G pipelines in Western Europe and North America (Cosham et al., 2007). The researcher has also taken other factors into consideration, such as vibrations and third party activities (Guo et al., 2005; Kishawy & Gabbar, 2010). Although advancements in metallurgical and manufacturing technologies have overcome some of these issues, maintenance strategies still play a key role in improving the reliability of pipelines and economically mitigating risks (Kishawy & Gabbar, 2010).

In this review, the pipeline inspection and maintenance policies are reviewed as and industrial assets as well as infrastructure assets. As an industrial asset, pipelines are considered as single unit repairable systems. Although no literature was found specifically on inspection and maintenance policies of the pipeline as a single unit, Hongzhou Wang (2002) presented a comprehensive review of the published literature on preventive maintenance policies for single unit systems. He identified age, the number of repairs or failure limit, time in service and condition of an asset as the main decision factors when selecting the inspection and maintenance policy. In recent research, “risk” is considered as main criteria for selection of inspection and maintenance intervals and policy. Most of the studies have presented risk-based inspection and maintenance (RBIM) policies to address issues related to maintenance of oil & gas pipelines (Arunraj & Maiti, 2007, 2010; Cosham et al., 2007; Dawotola et al., 2012; Prasanta Kumar Dey et al., 2004; Prasanta Kumar Dey, 2004; Hassan & Khan, 2012). The maintenance policies developed for O&G pipeline integrity management along with the risk-based policies are discussed in the following sections.

3.1 Corrective Maintenance

Corrective maintenance considered the most cost-effective policy where the maintenance actions are taken before the failure has occurred. However, the cost and benefits analysis between

CM and PM presented by Stenström et al.(2015), based on rail infrastructure case study, reveals that CM has 79-90% share of total cost whereas the PM maintenance has 10-30 % share. The analysis is based on historical data for inspection cost, repair, and maintenance of potential failure, repair of functional failure and cost due to loss of production. The unit stoppage under a corrective maintenance policy may be affordable in certain industries depending upon the mutual balance of production loss and unit replacement. Corrective maintenance as a policy might not be feasible for O&G pipelines due to nature of transporting material, loss of flow volume, and resulting environmental and financial consequences. For instance, repair of an offshore pipeline failure is inevitably challenging and time-consuming task. Deploying submarine repair equipment to fix the leak in an offshore pipeline is certainly very expensive. Also, such repair operations may take a long time, ranging from a few weeks to several months. However, corrective actions plans cannot be completely over-ruled being an integral part of maintenance policies in case of failure (Blanchard et al., 1995; Tsang, 1995).

Table 1 summarizes the applicability of existing maintenance policies on the type of assets. Age-based policies and failure limit policies have not been frequently reported in the context of pipelines. Due to the nature of pipeline operations and the economic and environmental consequences in case of failure, the condition based maintenance and the risk-based maintenance are more suitable policies.

3.2 Preventive Maintenance

In preventive maintenance policies, periodic repair or replacement is implemented when the unit is in operating conditions before failure. These policies are based on the scientific data analysis approach. Operation research methods were introduced in the PM policies for consistent decision-making (Ahmad & Kamaruddin, 2012). Moreover, most of the industrial preventive maintenance practices are relied on experts' experience and recommendations from the original equipment manufacturers (OEM) (Labib, 2004; Tam, Chan, & Price, 2006). The PM policies have further been classified by age, time in service, and a number of repairs or failures.

3.2.1 Age-based Policies

The main concept of this most commonly used policy is to replace the unit at a certain predefined age limit at time ‘T’ (Ahmad & Kamaruddin, 2012). While implementing the age-dependent policies the decision of maintenance or replacement is taken at age *T,* or if the failure of the unit occurs before age *T*. The unit is either maintained preventively at predetermined ages and is replaced only at the complete failure, or it is replaced at a predetermined age regardless of the condition and imperfectly maintained only if failure occurs before the replacement age (Barlow & Hunter, 1960; Hongzhou Wang, 2002). This type of maintenance is also known as imperfect maintenance. Repair actions such as welding of cracks, sleeves’ attachment to the eroded portions are considered as imperfect maintenance. The age of the unit is the most significant factor, but some studies presented the combined models of age-dependent policy and unit replacement policies at age T. During 1960’s, age-based policies were the most discussed; however, further extended models were developed between 1990 and 2000. These extended models are presented in Table 2.

3.2.2 Time in Service based Decision Policies

“Time in service” based policies were more frequently applied to repairable systems. One of the most discussed, Time in service based, policies is the periodic preventive maintenance policy (Yam, Tse, Li, & Tu, 2001). In the “Time in service” policies, preventive maintenance is scheduled at fixed intervals. The time interval is independent of the failure history of the unit. Chaudhuri & Sahu (1977) introduced the imperfect maintenance concept under the “Time in service” policies. Imperfect maintenance refers to the repair of the unit after which the unit is not considered as new but is supposed to be younger than before (Pham & Wang, 1996). Ahn & Kim (2011) presented a periodic maintenance policy to estimate the maintenance intervals based on the assumption that system exhibits a linearly increasing hazard rate and a constant repair rate. Certainly, the availability of a system increases with the shorter time interval between PMs and higher cost. The decision variables are periodic time, reference age and a number of repairs and failures. Further extensions of periodic PM policies are summarised in Table .

3.2.3 Failure/Repair Limit Based Decision Policies

Failure/ repair limits policies, first introduced by Bergman (1978), are the combination of imperfect maintenance and perfect maintenance policies. The general concept of these policies is to carry out imperfect maintenance until the unit reaches to a specific (predetermined) number of failure or repairs and then replace the unit. Due to imperfect maintenance, the policy maintains the acceptable level of reliability and unit remain in service till the defined level of reliability. Nakagawa & Osaki (1974) introduced economic factor in the policy that the unit should be replaced when the estimated cost of repairs exceeds the predetermined economic limit (Drinkwater & Hastings, 1967; Gardent & Nonant, 1963; Nakagawa & Osaki, 1974). Table 2 presents other models developed in this category. The discussed strategies, described above under the preventive maintenance policies, have the objective of reducing downtime and maintenance costs. Each policy has its advantages and disadvantages. Table 3 summarize decision criterion and actions suitable for repairable and non-repairable units under preventive maintenance policy.

To overcome the deficiencies of the police and maximise the effectiveness of the policy, researchers have devised hybrid policies by combining decision criterion and actions. Table describes the hybrid models in brief. For instance, Berg & Epstein (1976) combined the "age-based policy" with "time in service" policy along with the action of block replacement of the units. Later, Nakagawa (1981) adopted the same approach, but the action was the one-time replacement of the units. The most considering policy was a number of failure or repair limit policy, which was combined mostly with time in service policy and fixed cost policies, i.e., Morimura (1969), Nakagawa & Osaki (1974), Beichelt (1982), Stadje & Zuckerman (1990), etc. Most of the researchers considered the imperfect maintenance till the replacement limit reach and adopted one-time replacement of the unit. Y. Liu, Li, Huang, & Kuang (2011) presented an optimal imperfect sequential PM policy based on genetic algorithm for ensuring the consistency of the quality of maintenance activities. The variation in maintenance quality was considered as a stochastic variable at fixed time intervals. Figure 5 shows the decision process flow in preventive maintenance policies. For further discussion on hybrid policies, the readers are referred to Wang (2000) and Yu liu et al. (2011).

Preventive maintenance policies were not extensively used for O&G pipeline. Sun et al., (2014) suggested a time-based preventive maintenance (TBPM) strategy for individual pipeline based on the split system approach. They considered repair cost, PM cost, and the corrective repair cost as input factors for preventive maintenance policy. Expert opinion, historical industrial practice, and last repair were included as key factors for effective decision-making. The TBPM is implemented on a predefined segment of the pipeline at a prescheduled time to find the optimal start time and intervals between two PMs. The results revealed that within multiple constraints, TBPM policies based on the multi-objective optimization approach reduced the overall cost of maintenance.

3.3 Predictive Maintenance / Condition-based Maintenance

Condition-based maintenance (CBM) or condition based inspection and maintenance (CBIM), first introduced in 1975, use a condition monitoring / inspection process to improve decision making for preventive maintenance (Jardine, Lin, & Banjevic, 2006). The CBM/CBIM is the most well-known and discussed maintenance policy in literature published since 2000 (Ahmad & Kamaruddin, 2012; Grall, Bérenguer, & Dieulle, 2002; Han & Weng, 2011; Moya, 2004). CBM assumes that a system subjects to a random deterioration process. The main objective of the CBM is to perform a real-time assessment of the equipment to enhance its reliability and to reduce the unnecessary maintenance costs (Gupta & Lawsirirat, 2006). Generally, in the CBM policy, the condition of the system is monitored through perfect inspection at regular intervals. The condition analysis is used for future maintenance decisions (Zio, 2012). The condition monitoring / inspection processes are conducted in two ways: an online process during operation and an offline process during shutdown time. The intervals for this process can be determined on fixed, continuous, or risk basis. Continuous monitoring can be highly expensive (Jardine et al., 2006); therefore, in most cases equipment failure is assessed based upon certain conditions, signs or indications (Bloch, 1998). The details of condition monitoring methods have already been discussed in section 2.3

Maintenance decisions under the CBM policy can be classified as diagnostic and prognostic. The diagnostic process is the process used to find the cause and source of the fault (Jeong, Leon, & Villalobos, 2007); whereas in the prognostic approach, the causes of failures are identified using predictive methods (Lewis & Edwards, 1997). The diagnostic approach provides an early warning to management about failure. Sometimes, abnormal behaviour of equipment does not show any sign of failure; in this case, equipment performance seems satisfactory until complete failure. In such cases when the diagnostic approach is unable to predict the failure, the prognostic approach can predict the failure before its occurrence. The prognostic approach can be more cost-effective as it facilitates better planning and maximum utilization of equipment and prevents unexpected failure (Ahmad & Kamaruddin, 2012).

A detailed review of CBM policies can be found in Ahmad & Kamaruddin (2012). Reduction of CBIM cost depends upon inspection intervals and critical replacement threshold values (Grall et al., 2002).

3.3.1 Estimation of inspection intervals

A selection of optimal inspection intervals is a basic challenge in predictive maintenance policy. In the past, industry used to set inspection intervals based on in-service time and calendar dates (i.e., the fixed shutdown dates based on production schedule and availability of the resources) (API, 2009). With experience, the periodic inspection of an entire pipeline was not found to be a feasible method. According to API codes the inspection frequency of pipelines is determined on the basis of transporting fluids types or half remaining life of the pipeline (Chang et al., 2005). Several qualitative and quantitative models have been developed to determine the optimal inspection and maintenance intervals, so far. Different researchers have suggested various inspection interval models based on the optimization of cost and the integrity of the pipeline. Grall et al. (2002) presented CBM for a random and continuously deteriorating single unit system where replacement threshold and inspection intervals were considered as decision variables. They assumed that the system was under random deterioration and inspected by perfect inspection. They modeled the maintenance cost through a stochastic model based on the stationary law of the state of the system. Although the study did not discuss a real maintenance case, such mathematical models can help to take better maintenance decisions. In regards to CBM, most studies used condition data recorded by the diagnostic systems to decide the maintenance intervals, but few studies took the cost in consideration. Tien et al. (2007) suggested that the internal condition of pipelines should be assessed at least once a year (Tien, Hwang, & Tsai, 2007). Opila & Attoh-

Okine (2011) used a mean time of failure, based on a scoring approach time interval, for structural inspection/condition monitoring of pipelines. The mean time to failure describes the expected time to failure for a non-repairable system. The approach is easy to use and provides simple interpretation and validation for pipe conditions. Pandey (1998) presented reliability based probabilistic models to determine the optimal inspection interval and to achieve targeted reliability with economic considerations. D. M. Frangopol & Liu (2007a) used dynamic programming procedure integrated with Monte Carlo simulations for bridge network maintenance optimization. Kim, Frangopol, & Soliman (2013) presented a generalized probabilistic framework for optimal inspection and maintenance planning of deteriorating structures. Goems & Beck (2014) employed multi-start simplex optimization method for optimizing the time of first inspection and inspection intervals. The results of the model were compared with over inspection process results. The models results show the nine and half time optimization in inspection intervals.

Condition based maintenance policies are less discussed for Oil & Gas pipelines in the literature. The condition based policy is focused on the system's reliability instead of the impact of failure consequences on the environment and humans. However, condition assessment results are used for risk evaluation, which is a key component of proactive maintenance policies. The integration of the consequences of failure with condition based maintenance laid the foundation for proactive maintenance policies. The proactive maintenance policies will be discussed in the following section.

3.4 Proactive Maintenance / Risk-based Maintenance

Risk management is a systematic approach to characterize existing system risk, decrease the probability of harmful events and/or to reduce the harmful consequences of the occurred events (Opila & Attoh-Okine, 2011; V. P. Singh, Jain, & Tyagi, 2007). A typical risk assessment model begins with hazard identification followed by the modeling of causes, estimation of the likelihood of effects and estimation of impacts by qualitative, quantitative or semi-quantitative methods. Risk models estimate absolute and relative risk, major risk contributors and compare risk factors. Stages of risk analysis are hazard analysis, consequence estimation, likelihood estimation, risk estimation, risk acceptance criteria and maintenance planning. Geary (2002) reported that 50% of British companies use risk-based inspection approaches. Since 2000, the terms risk-based inspection

(RBI) and risk-based maintenance (RBM) have been used interchangeably. However, recently a new generation of terminologies have been adopted, such as reliability-centered maintenance and condition-based maintenance (CBM). Therefore, risk-based maintenance and risk-based inspections are not the separate topics anymore. Both the terminologies are referred to the same set of actions (Tan et al., 2011).

Risk-based inspection and maintenance (RBIM) is a relatively recent approach to pipeline integrity management and can be considered as an extension of the condition based maintenance policy. RBIM is a need-based strategy to prioritize an inspection and maintenance plan based on risk ranking; it helps managers to execute informed testing and inspection without affecting public safety (Dawotola et al., 2012). High-risk components or units have to be inspected with greater frequency and intensity (Tan et al., 2011). The RBIM priority is determined by the likelihood of failure and consequence of failure (Chang et al., 2005). Reliability standards are set as a function of time and compared with reliability levels while taking maintenance decisions (Nessim, Yue, & Zhou, 2010). Industrial standards such as API 580, ASME B31.8S and CSA Z662 Annex O describe the risk/reliability-based design and assessment methodologies (Nessim et al., 2010). The American Petroleum Institute standard (API) 580 defines risk-based inspection as, *"[a] risk assessment and management process that is focused on the loss of containment of pressurized equipment in processing facilities, due to material deterioration. These risks are managed primarily through equipment inspection."* RBI is based on an assessment of the probability of occurrence, their severities, and consequences (API-580, 2009; Chapman, 1997; Lawrence, 1976; Tan et al., 2011; Tien et al., 2007). Different risk-based maintenance techniques discussed in the literature for each stage of risk analysis are classified in Table .

Qualitative, semi-quantitative, quantitative are the techniques for risk analysis (Han & Weng, 2011); whereas probabilistic, deterministic, and their combination are different methodologies for risk estimation. Deterministic methodologies are based on the assumption that occurrence of a hazard and its consequences on people, environment and equipment are well-known and certain. Conversely, a probabilistic approach is based on the probability of occurrence of a hazardous event or potential accident. Probabilistic models have a tendency to ignore the low probability situations that can be misleading. On the other hand, a possibilistic approach incorporates low possible events; however, the approach is too subjective and may also give imprecise results (M. Singh & Markeset, 2014a, 2014b, 2014c). The cross-classification in qualitative, semi-quantitative, quantitative models is based on quantitative data or qualitative judgement of experts (Arunraj & Maiti, 2010). Figure 6 outlines the qualitative and quantitative processes of risk assessment. Qualitative techniques are used to identify and to model the cause and effect of the hazard. The output is a qualitative ranking for the recommendations of hazard identification and control. Quantitative techniques are used to estimate the likelihood and the impact. The output is a quantified benefit and cost of risk reduction alternatives. The quality of risk analysis is based on: hazard identification and initial consequences analysis; type of analysis (qualitative or quantitative) and the factors such as frequency estimation, uncertainty, and sensitivity analysis (Arunraj & Maiti, 2007).

Table presents the most commonly used techniques for risk analysis in O&G industry.

The RBIM approach has been successfully used for the maintenance decisions for mechanical and civil infrastructure, onshore and offshore structures, and cross-country pipelines (Al-Khalil, Assaf, & Al-Anazi, 2005; Prasanta K Dey, 2001; Prasanta Kumar Dey et al., 2004; Prasanta Kumar Dey, 2003, 2004; Famurewa, Asplund, Rantatalo, Parida, & Kumar, 2015; Rangel-Ramɪrez & Sørensen, 2012). The inspection is an integral part of RBIM. The integrity and safety of the structure is related to the quality of inspection in terms of detectability and size of damage; however, over-inspection may enhance the unnecessary cost of inspection. Moan (2005) presented reliability based I&M for off shore structures such as production platforms, ships, semi-submersible, jack up, Jacket affected by crack growth and corrosion. In addition, design allowance against the corrosion and accidental collapse limit state were also included for reliability analysis. Rangel-Ramɪrez & Sørensen (2012) developed a probabilistic model for I&M of offshore wind turbines. Fatigue and corrosion control were considered as main contributing factors in risk analysis. Famurewa et al. (2015) used a risk-based approach to analyse the maintenance performance of railway infrastructure. Risk of failure of punctuality, operational capacity, economic and safety were considered as primary decision factors in their study. El-Abbasy, Senouci, Zayed, Mirahadi, & Parvizsedghy (2014) presented condition assessment model by using historical inspection data of pipelines in Qatar by using regression analysis.

Pipeline failure can never be completely controlled, but overall risk can be reduced to *"as low as reasonably practicable"* (ALARP). The risk is considered to be ALARP if additional mitigation cost is not proportionally advantageous to the benefits achieved (F. Khan et al., 2004; Shahriar et al., 2012). A number of qualitative, semi-quantitative, quantitative methodologies have been used for the RBIM of oil and gas pipelines (e.g., hazard and operability study (HAZOP), failure mode and effect analysis (FMEA), fault tree analysis (FTA), event tree analysis (ETA)) (Arunraj & Maiti, 2007; Han & Weng, 2011; F. I. Khan & Abbasi, 2001; Miri Lavasani, Wang, Yang, & Finlay, 2011; Shahriar et al., 2012). The available industrial standards for risk-based inspection and maintenance mostly used qualitative models. American Petroleum Institute's risk-based inspection guidelines (API-580, 2009) used an approach of absolute "risk number" for qualitative or semi-quantitative risk analysis.

Analytical hierarchy process (AHP) has been one of the most frequently applied multiple attribute decision making technique in RBIM (Al-Khalil et al., 2005; Arunraj & Maiti, 2007, 2010; Cagno, Caron, Mancini, & Ruggeri, 2000; Prasanta K Dey, 2001; Prasanta Kumar Dey et al., 2004; Prasanta Kumar Dey, 2003, 2004; Tan et al., 2011). AHP employs a subjective, and qualitative pairwise comparisons approach based on expert opinion to derive priority scales for alternatives (Thomas L Saaty, 2008; Thomas Lorie Saaty, 1996). In RBIM, the impact or consequence of an event is aggregated based on expert opinion for AHP application (Al-Khalil et al., 2005; Prasanta Kumar Dey et al., 2004; Tan et al., 2011). The models used a likelihood loop considering several failure factors such as corrosion, external interference, and construction and material defects. The models included different consequences in case of natural disasters, such as loss of production, loss of commodity, loss of life and property, loss of the image of a company, and environmental damage. Inline inspection, cathodic protection survey, patrolling, contingency plan, improved instrumentation, pipe coating and pipe replacement were the suggested inspection and maintenance methods for onshore pipelines (Prasanta K Dey, 2001), in addition, remotely operated vehicles, acoustic survey and diving were the suggested methods for offshore pipelines (Prasanta Kumar Dey et al., 2004).

The fuzzy logic approach has extensively been reported in the literature to handle imprecise information and variation in expert opinion. This methodology is effective to reduce dependence upon precise data and can give better understandings of linguistic data (M. Singh & Markeset, 2009). Risk analysis integrated with fuzzy set theory overcomes the uncertainties associated with the conservative assumptions made by the experts in AHP (F. Khan et al., 2004). The neural networks have also been used for RBIM; however the adequacy of such models depends upon the quality of historical data, i.e., outliers and noise in the data can cause prediction errors (Najafi & Kulandaivel, 2005). The probability of failure and associated consequences are also determined by fitting historical data of failure into either a homogeneous Poisson process or non-homogeneous Poisson process (Dawotola et al., 2012). Details related to limitations, and pros and cons of these methods are discussed in the following section 3.5.

Figure 7: Evolution of different types of maintenance policies showing number of studies reported in literatureshows the distribution of the published literature on inspection and

maintenance policies in the past. It can be seen in the figure that until the end of 19th century, the primary focus was on maintenance, reliability, and availability of the system. Meanwhile, the high cost of maintenance (i.e., primarily replacement) shifted the direction of research to predictive and proactive policies. The figure also reveals that since 2000, the primary focus of the research was proactive or risk-based I&M policies. However, during this era, some researchers also tried to resolve I&M issues using the earlier approaches. Zio (2012) compared different maintenance policies by using an example of fatigue degradation process of mechanical components. He concluded that Although CBM and proactive maintenance have better performance, it cannot be generalized due to the fact that in certain situations traditional CM and PM work more efficiently than CBM and proactive maintenance. For example, in cases when the cost of corrective maintenance in the response to incidents or the cost of frequent inspection are more than the operational cost. The suitability of different approaches for O&G pipelines is evaluated in Table 6. Based on the evaluation parameters, i.e., assessment criteria, decision criteria, pros and cons, it can be concluded that proactive or risk-based maintenance policies are most suitable for O&G pipelines.

3.5 Decision-making challenges under Uncertainties for Proactive Maintenance Policies

This section addresses the uncertainties influencing the effectiveness of decision-making process for risk-based maintenance policies, e.g., uncertainties in internal and external degrading process, variability in inspection results, conservative assumptions for unknown data, the subjectivity of the decision-maker opinion, budgeting and costing for maintenance and imperfections in the investigation and prediction of defects. Availability and accuracy of inspection and operational data may significantly influence the decision-making process (Ahmadi, Cherqui, De Massiac, & Le Gauffre, 2015). Both probabilistic and statistical approaches have been used to deal with uncertainties in degradation process (Elnashai & Tsompanakis, 2012; Kim et al., 2013; Rangel-Ramırez & Sørensen, 2012). Financial constraints and uncertainties due to variation in limited budget of maintenance was also taken into account (D. M. Frangopol & Liu, 2007a; Kim et al., 2013).

The epistemic uncertainties are associated with material defects, loads, and damages. Kim & Frangopol (2012) presented a probabilistic approach for I&M planning to handle such uncertainties related to fatigue crack initiation, propagation and damage detection in naval ships, and bridges subjected to fatigue. The uncertainties in risk-based decision makings regarding the design, fabrication, and operation of offshore structures were addressed by (Moan, 2005). D. M. Frangopol & Liu (2007b) reviewed the development in lifecycle maintenance planning using genetic algorithms for civil infrastructures and associated uncertainties in the degradation process. D. M. Frangopol & Bocchini (2012) discussed the uncertainties associated with limited financial resources and multi-disciplinary coordination for maintaining of bridges. The combination of stochastic expansions for probabilistic uncertainty with optimization approach provides both the accuracy and efficiency (D. Frangopol & Tsompanakis, 2014). Parvizsedghy et al. (2014) presented fuzzy based maintenance decision support system to address the uncertainties related to operation and maintenance cost estimation and other economic aspects. However, data with a certain amount of uncertainty is preferable than incomplete data obtained from pipeline inspection (Ahmadi et al., 2015).

In this paper, fifty articles published on the risk-based pipeline maintenance policies are reviewed, and uncertainties are grouped under four classifications: i) data limitations in quantitative models, ii) lack objectivity in qualitative models, iii) investigation and prediction of defects, and iv) variability in inspection results. Figure 8 shows that most of the research are carried out to deal with the uncertainties associated with investigation and prediction of defects as compared to the uncertainties due to lack of availability of data for quantitative models and subjectivity of expert opinion in qualitative models. Although very few articles addressed the issue of variability of inspection results (M. Singh & Markeset, 2014a, 2014b, 2014c), it is the most recent focused area in risk-based maintenance policies. All the uncertainties mentioned above are discussed in more detail in the following.

3.5.1 Lack of data in quantitative models

Sufficient data about population density, economic condition, pipeline operation parameters, wall thickness and historical accident data is required to estimate importance (weights) of the inherent risk index and the consequence index. Such data is difficult to obtain (Bartenev, Gelfand, Makhviladze, & Roberts, 1996). Deng (1989) used Grey correlation theory to overcome this issue. The theory aims to find the co-relation in dissimilar data assuming that the correlation depends upon the similarity of the geometric shape of the data series curves. Furthermore, in the data preprocessing the dimensionless transformation is used to convert the original sequence of the data into a comparable sequence (Han & Weng, 2011).

The historical accident data has been used to determine failure rate of pipelines for empirical models; however, the limitations in available accident data increases the uncertainty of the model results (Jo & Ahn, 2005; Jo & Crowl, 2008). Han (2011) presented a comparative analysis of qualitative and quantitative risk models for urban gas pipeline networks based on historical records of accidents. For the qualitative method, statistical analyses of accidents databases were used to develop the indices based on the Grey correlation and the reliability engineering theories. The causes of failure were categorized into four levels of indices by assuming the equal contribution of the causation index and the consequence index to risk quantification. However, such long-term historical data might not always be available. Simonoff et al. (2010) modeled cost consequences in natural gas transmission and distribution; however the fatalities and injuries were not considered due to lack of data. Dawotola et al. (2009) estimated the probability of failure by fitting historical records of pipeline failure due to stress corrosion cracking. The issue is addressed by using homogeneous Poisson process assuming, corrosion as a uniform process, pipeline system to be restored as new after minimal repair, and that the repair did not affect the pipeline failure frequency or homogeneity in the pipeline segment. Such assumptions may not be accurate for all segments of the pipelines and limit the confidence of the model. Furthermore, the model does not accommodate changes in maintenance history, which may have an impact on failure frequency. The prediction models trained on historical inspection and maintenance data of assets have limitations that they can only assess and predict the future condition of the same asset (El-Abbasy et al., 2014).

3.5.2 Subjectivity in qualitative models

Decisions about inspection and maintenance intervals are very subjective. The most of the models presented about decisions of inspection and maintenance interval are qualitative models. The qualitative methods are subjective and sensitive to the extent of the experience and knowledge of the decision makers; such a subjectivity may lead to large variations in the results. F. Khan et al. (2004) highlighted the flaws in the qualitative or semi-quantitative approaches, including variation in selection of failure mechanism, variation in conclusion, averaging of all consequences, neglecting the impact of individual consequences, difference in contents of inspections and inspection intervals, and subjective judgement due to limited information about failure knowledge. Most typical approach to developing decision support model by ranking the expert opinion for pipelines is the analytical hierarchy process (AHP) and the weighted average technique (Dawotola et al., 2012; Prasanta K Dey, 2001; Prasanta Kumar Dey et al., 2004; Prasanta Kumar Dey, 2003, 2004). Due to the subjective nature of AHP, it yields different results under different judgements for the same problem (Arunraj & Maiti, 2010; Nyström & Söderholm, 2010; Thomas L Saaty, 1990).

Probabilistic frameworks and models have also been reported in the literature to deal with the subjectivity of qualitative models. F. I. Khan & Haddara (2003) presented a quantitative approach based on a predefined threshold as a criterion for risk-based maintenance to overcome inherent uncertainties. Fault tree and reverse fault tree analysis were used to estimate the time interval between the inspection/maintenance tasks. F. Khan et al. (2004) adopted the Weibull distribution to determine inspection intervals and found that the overall risk decreases at a slower rate with the decrease in the likelihood of failure. Although the fuzzy-based approach accommodates variation in the decision results; the robustness of the analysis is subjected to the expert experience and judgment.

3.5.3 Investigation and prediction of defects

Identification of the uncertainties associated with the prediction of defect growth and with the effect of the defect on the integrity of pipelines is a challenging task (M. Singh & Markeset, 2009). The time lag between the occurrence of a failure event and the resulting consequences further increases the vagueness in forensic investigation. Traditional methodologies do not take the multi-dimensional consequences into account (Brito et al., 2010). The researchers used multiple techniques to address the uncertainties due to lack of knowledge of defect prediction by using conservative assumptions made by the experts and linguistic expressions. For instance, Sawyer & Rao (1994) presented a fuzzy fault tree technique for the reliability analysis of mechanical systems. Later, Cheng (2000) proposed evidence theory to address the uncertainties in fault tree analysis. Huang, Chen, & Wang (2001) evaluated human errors and integrated them into event tree analysis by using fuzzy concepts. Sentz & Ferson (2002) presented the Dempster-Shafer theory, as an alternative to traditional probabilistic theory for the mathematical representation of uncertainty. Wilcox & Ayyub (2003) suggested that fuzzy and interval representations are appropriate techniques to address uncertainties when data is subjective, vague, or cognitive. M. Singh & Markeset (2009) used a fuzzy-based inspection model for corrosion rate assessment. Shahriar et al. (2012) have addressed the issue of uncertainty with the help of fuzzy based bow-tie analysis (Cockshott, 2005; De Dianous & Fiévez, 2006; Duijm, 2009; Markowski, Mannan, & Bigoszewska, 2009; Shahriar et al., 2012) by combining fault tree analysis (FTA) and event tree analysis (ETA). FTA and ETA are qualitative analysis techniques of hazards identification and quantitative risk assessment of undesirable incidents (Spouge & others, 1999). Traditionally Bowtie analysis requires precise data or defined probability density functions (Markowski et al., 2009). Such data are not easy to acquire in the case of pipeline risk analysis due to inherent uncertainties of design and material faults, limited understanding and vagueness of failure mechanisms (Ayyub, 1991; Ferdous et al., 2009; Sadiq et al., 2008; Sawyer & Rao, 1994; Yuhua & Datao, 2005).

Triangular fuzzy numbers have been used to assess the failure probabilities associated with pipeline installation, manufacturing of pipe, quality of welding, and percentage of inclusions (Yuhua & Datao, 2005). Shahriar et al. (2012) integrated the fuzzy rule base and fuzzy synthetic evaluation to evaluate the triple bottom line sustainability criteria and to analyse the influence of interdependencies among the various factors, such as construction and material defects, incorrect operations, outside forces and corrosion, on the analysis results. The model can help the decision makers for informed decision-making by considering multi-dimensional consequences that may arise from pipeline failures.

Brito et al. (2010) proposed the multi-criteria model based on *ELECTRE TRI* integrated with utility theory for qualitative and quantitative risk analysis of natural gas pipelines. The integrated model evaluates the uncertainties for different scenarios using *ELECTRE TRI* and aggregates the decision maker's preferences regarding human, environmental and financial risks with the help of utility theory.

Sahraoui et al. (2013) developed a Bayesian formulation based probabilistic approach to addressing different inherent uncertainties related to inspection methods. They integrated imperfect maintenance results in the cost model for corroded pipelines. The failure probabilities, as a function of pipe age, were used for reliability analysis. The numerical application shows the effect of inspection quality and cost on maintenance planning. The imperfect maintenance may lead to wrong decisions about cost and safety. Optimal maintenance interval is dependent on corrosion rate.

Aven & Zio (2011) presented a framework for including uncertainty in risk assessment by critically analyzing alternative approaches and seeking their coherent integration for effective decision making beyond the Bayesian approach. They argued that the risk-uncertainty description is more than subjective probabilities and highlighted some key issues such as: how completely realistically the analysis represents the knowledge and information available?; how costly is the analysis?; how much confidence does the decision maker gain from the analysis and the presentation of the results?; and what value does it bring to the dynamics of the deliberation process?. However, if uncertainty is not properly treated in risk assessment, the risk assessment tool fails to perform as intended. Table 7 classifies the uncertainties and their solutions presented in the reviewed literature.

3.5.4 Variability in inspection results

The ability to accurately measure the rate of corrosion growth along a pipeline is an essential input for integrity management decisions. For example, corrosion rates are essential to predict the condition of pipeline and to determine the suitable interval of inspection and maintenance (Nessim, Dawson, Mora, & Hassanein, 2008). Variability in the inspection results may affect the maintenance decisions. The term “variability” describes deviation of measured data from its mean due to the non-uniform condition of the pipeline dimensional parameters (diameter and wall thickness) and variation in the location, length and depth of the corrosion pits. In contrast, uncertainty is the variation in measured results due to the operator’s skill, inherent characteristics of the measuring instrument and operation.

Nassim et al. (2008) discussed the uncertainties related to measurements which are essential to estimate corrosion size from ILI runs; i.e., consecutive ILI runs have a degree of uncertainty while calculating corrosion growth rate. This uncertainty should be considered to estimate valid and accurate corrosion growth rates. The ratio between the measured corrosion growth and the measurement error is an important parameter in determining a meaningful distribution of the corrosion growth rate. The small ratio may refer to a large uncertainty which can lead to erroneous probabilistic inferences. The large ratio value makes the effect of measurement uncertainty more manageable and allows the growth rate distributions to be calculated with reasonable confidence.

The capacity equation is a mathematical model used to estimate the remaining pressure capacity of the pipeline after the initiation of corrosion defect. DNV recommended practices (DNV RP-F101) cater for uncertainties in inspection process related to defect depth by incorporating safety factor in the capacity equation. Unlike conventional safety factor, this approach depends upon inspection tool accuracy (i.e., dispersion of corrosion growth rate and metal loss data). Noor, Ozman, & Yahaya (2011) have manipulated DNV RP-F101 polynomial equation to predict future growth of defects by deriving a time function standard deviation equation of inspection tool. The future predicted metal-loss data is supposed to have higher variation from its central tendency value compared to actual metal-loss data. This approach gives a more realistic assessment of pipeline condition due to rapid reduction of structure capacity.

Hallen, Caleyo, & Gonzalez (2003) presented a probabilistic analysis framework to address the variability associated with inspection data gathered by inline inspection tools. In this framework, the data combined with fitness-for-purpose probabilistic assessments using the structural reliability analysis (SRA) method computes the pipeline failure probability with time. Target reliability levels were used as a reference to assess the condition of the pipeline as measured by its failure probability model (Nessim, Zhou, Zhou, & Rothwell, 2009). The comparison helps the decision makers to establish the best cost effective and safe maintenance policy for the future structural integrity of the pipeline. M. Singh & Markeset (2014b) have discussed the imperfection in inspection results due to several reasons, such as instrumental variability, complexities in operating conditions and the random nature of system variables. They also addressed the issue of imperfections in inspection results by combining probabilistic and the possibilistic approaches, i.e., fuzzy probability distribution function of the inspection data.

Table summarised the uncertainties, their causes and solutions presented by researchers. Out of fifty studied studies, twenty-five addressed the oil and gas pipelines, fifteen articles addressed only oil pipelines, and ten articles were specific to gas pipelines.

4 Summary and Conclusions

The review focuses on peer-reviewed literature published for inspection and maintenance policies for oil and gas (O&G) pipelines. More than a hundred research articles were reviewed to understand the evolution of maintenance policies, their implementation, and associated issues for O&G pipelines. It was found that 50% of the studies were related to both the O&G pipelines, 30% accounted for oil pipelines only, and the remaining were specific to gas pipelines. Gas pipelines are single-phase flow pipelines, whereas oil pipelines are three phase flow pipelines. The internal and external threats affects the integrity of O&G pipelines. The studies revealed that oil pipelines are more vulnerable to failure due to internal corrosion as compared to gas pipelines. The failure of gas pipelines may have widespread consequences due to rapid spread in the environment; however, failure of oil pipelines may have long-lasting environmental effects. Integrity can be improved by inspection, testing, and analysis followed by appropriate and timely maintenance. A good maintenance decision means the selection of the right pipe at the right time and the application of the optimal maintenance strategy and technology in a cost effective manner.

This review of literature broadly categorises the maintenance policies as corrective policies, preventive policies predictive policies, and proactive policies. Maintenance decisions help to overcome the possible threats of failure due to metal loss, external damages, manufacturing errors, human operational mistakes and the age of the asset. Therefore, implementation of the maintenance policies is a multi-criteria decision process. Corrective maintenance policies were implemented in the early 1940s based on the principle of "*repair when broke*. In the early 1950s, it was determined that repair after failure is not a feasible policy, particularly for oil and gas pipelines due to severe economic and environmental impacts in case of failure. Meanwhile, awareness about environmental concerns led to environmental protection laws that compelled the pipeline operators to maintain safe and leak-free pipeline operations. As a result, the 1960s can be considered the era of preventive maintenance policies which adopted the concepts of preventive overhauls, i.e., repair of equipment/unit at fixed and scheduled intervals depending upon age or time. Incorporating the condition assessment results transformed preventive maintenance into predictive or condition-based maintenance in the 1990s. This review also reveals that predictive maintenance policies improved cost effectiveness in the decision-making process for integrity management of O&G pipeline industry.

Since 2000, the integration of likelihood of failure and the resulting consequences shifted the predictive maintenance into proactive maintenance policies (i.e., also known as risk-based maintenance (RBM) policies). RBM policies for O&G pipelines are the most discussed in the most recent literature. A number of qualitative, semi-quantitative, and quantitative methodologies for RBM were reported in the literature. Deterministic and probabilistic methods and their combinations are the techniques used for risk analysis. However, expert judgement is the factor that most significantly influences the results of risk analysis. The reported issues related to the implementation of RBM policies include uncertainties and variability, conservative assumptions, the subjectivity of the decision-makers' opinions, and imperfections in the inspection data. In this paper, more than 50 articles covering RBM policies have been reviewed, and uncertainties are categorised into four types: i) uncertainties due to lack of data in quantitative models, ii) subjectivity in qualitative models, iii) investigation and prediction of the defect, and iv) variability of inspection results.

The review revealed that about 50% of the studies on RBM policies addressed the uncertainties associated with investigation and prediction of defects, followed by 24% studies that took into account the uncertainties due to subjectivity in qualitative models. So far, uncertainties due to the variability of inspection results are the least (i.e., 8%) addressed in published literature. The primary focus of most of the existing studies is on reducing the probability of structural failure and reducing repair and maintenance costs. O&G pipelines pass through diverse land uses and environmental settings ranging from ecologically sensitive natural areas to densely populated urban areas, and may have severe, long-term, and irreversible impacts in case of pipeline failure.

In this regard, a relatively less addressed issue in RBM policies is consideration of environmental and land use related factors for estimating the consequence part in overall estimated risk

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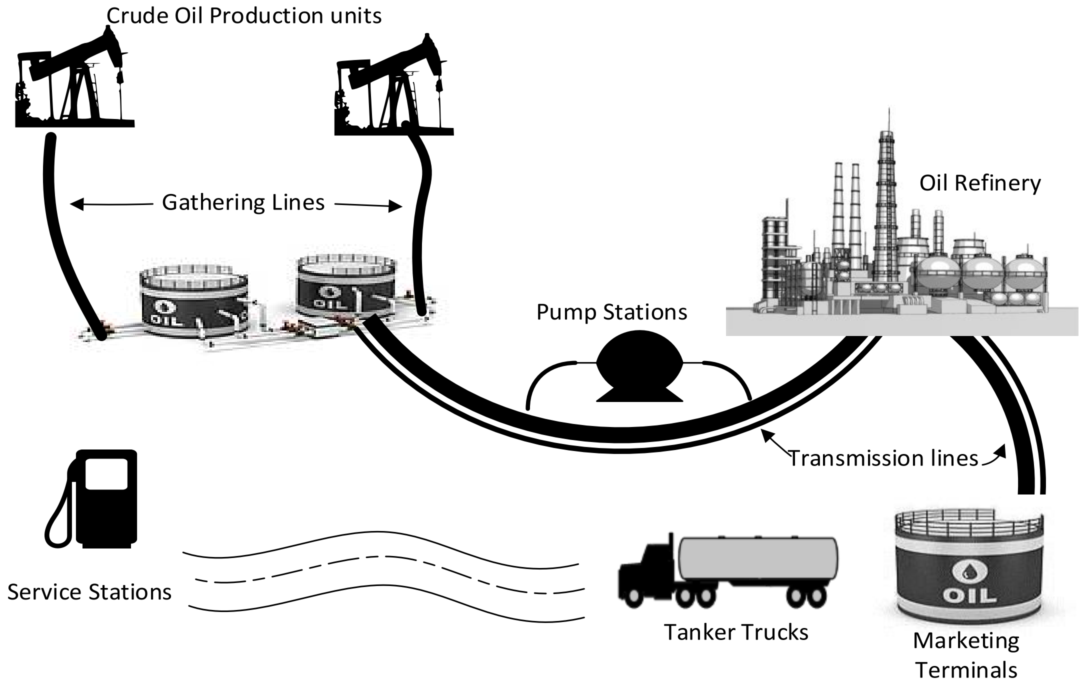
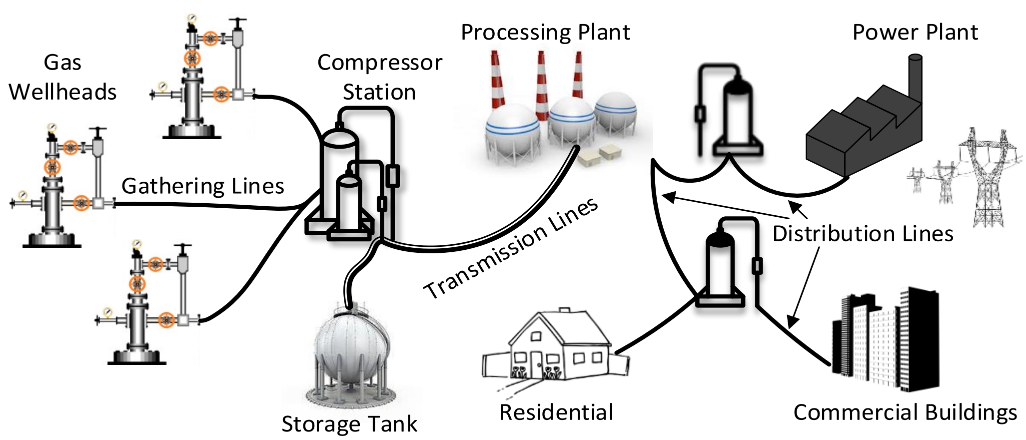


(a)



(b)

Figure 1: Oil and gas pipeline system: a) Oil pipeline system b) Gas pipeline system, adopted from CEPA (2015)

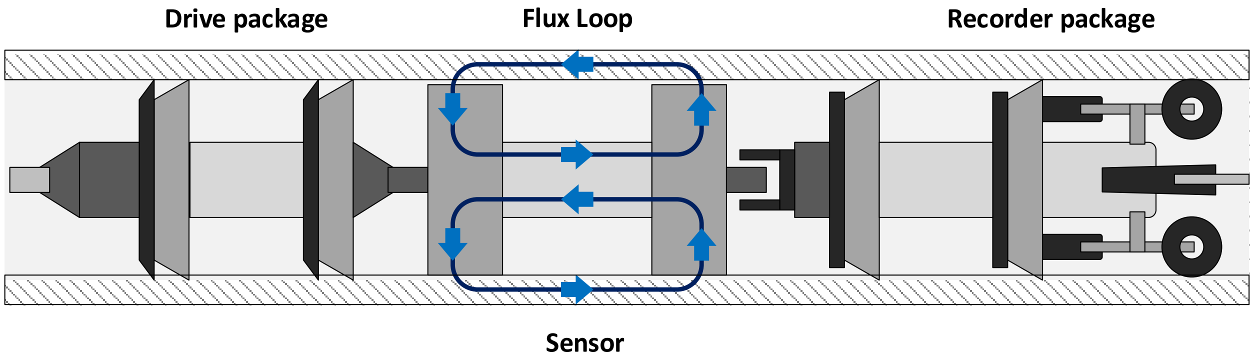


Figure 2: Main components of magnetic flux leakage type smart inspection PIG reproduced from Non-destructive Testing Resource Center (2015)

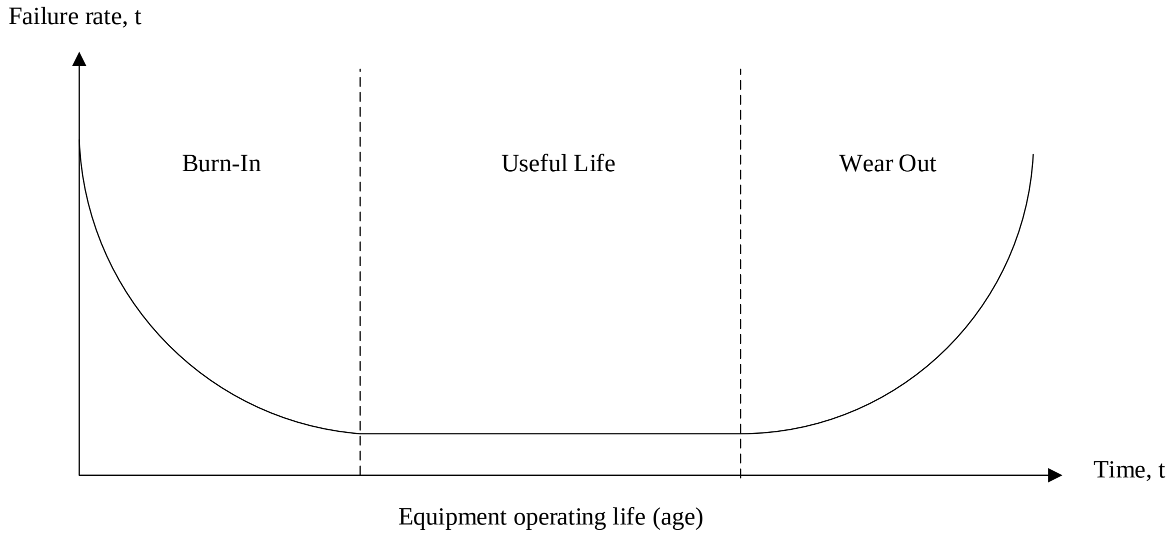


Figure 3: Bathtub curve showing traditional behaviour for equipment life cycle adopted from (Ahmad & Kamaruddin, 2012)

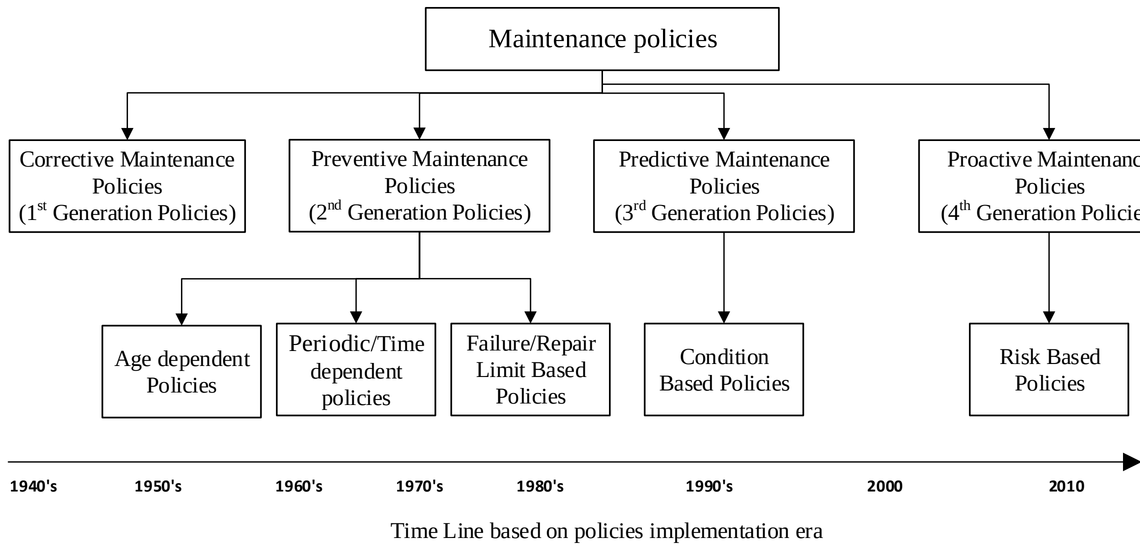


Figure 4: Evolution of maintenance policies for assets from 1940 to present

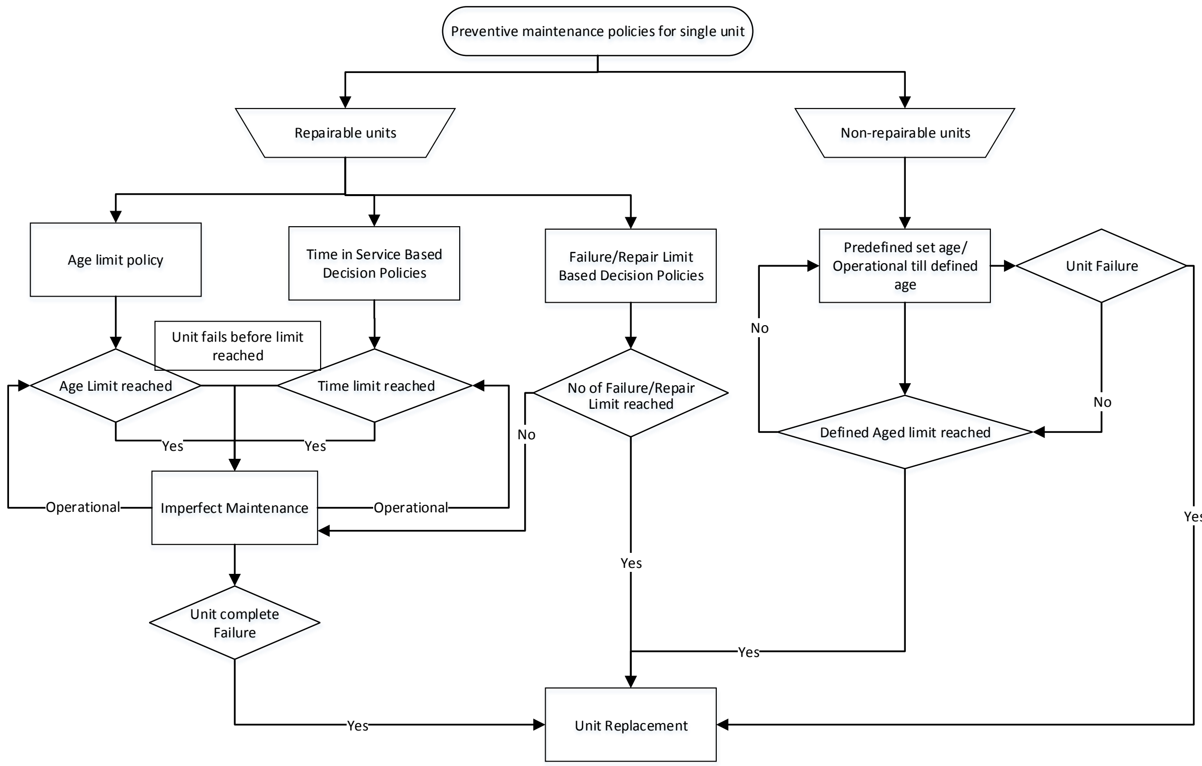


Figure 5: Decision process-flow diagram for preventive maintenance policies

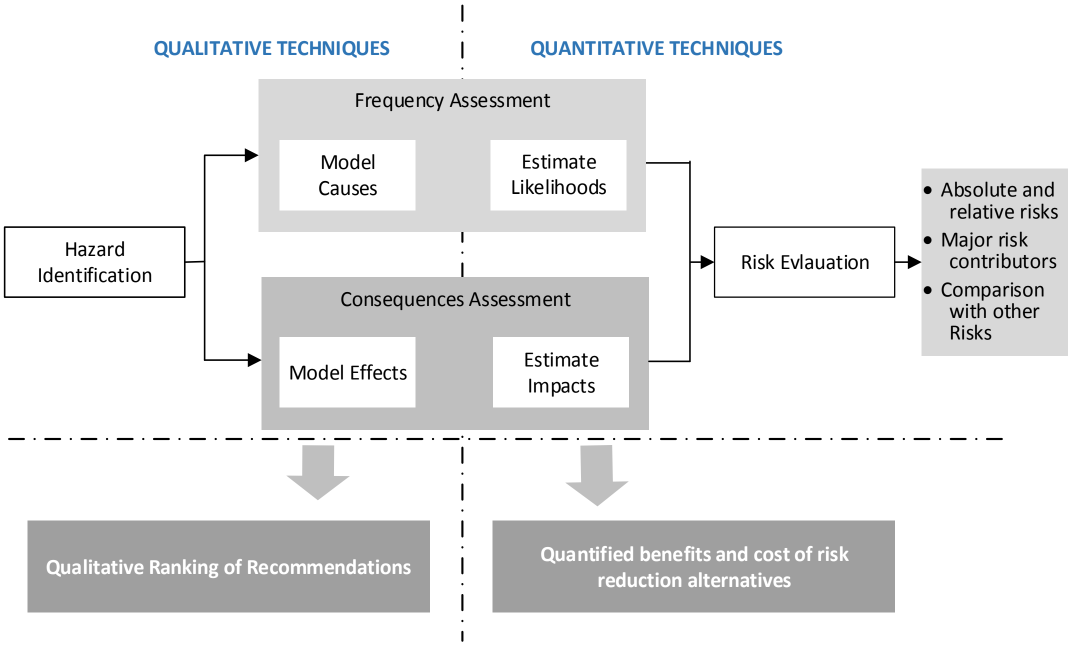


Figure 6: The process of risk assessment adopted from Arunraj & Maiti (2007)

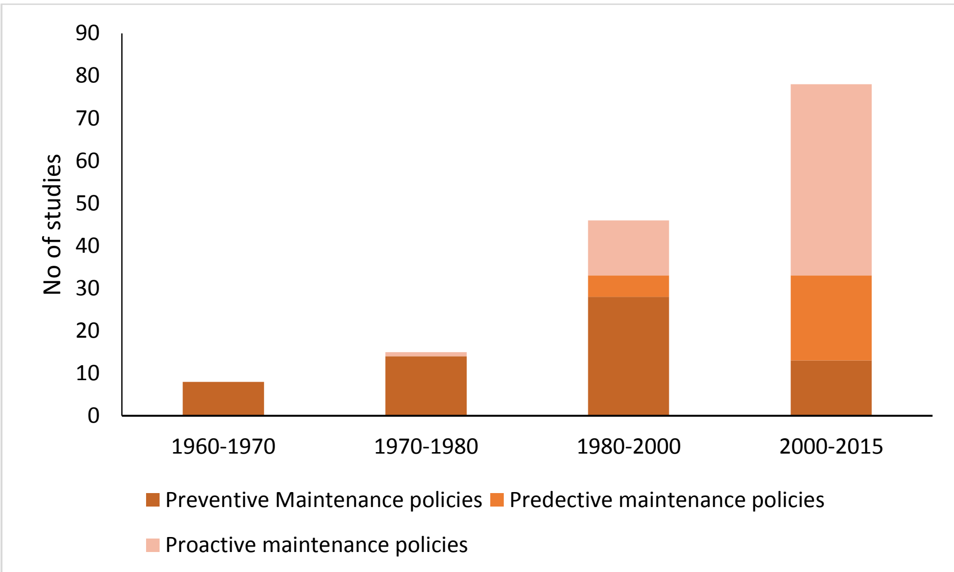


Figure 7: Evolution of different types of maintenance policies showing number of studies reported in literature

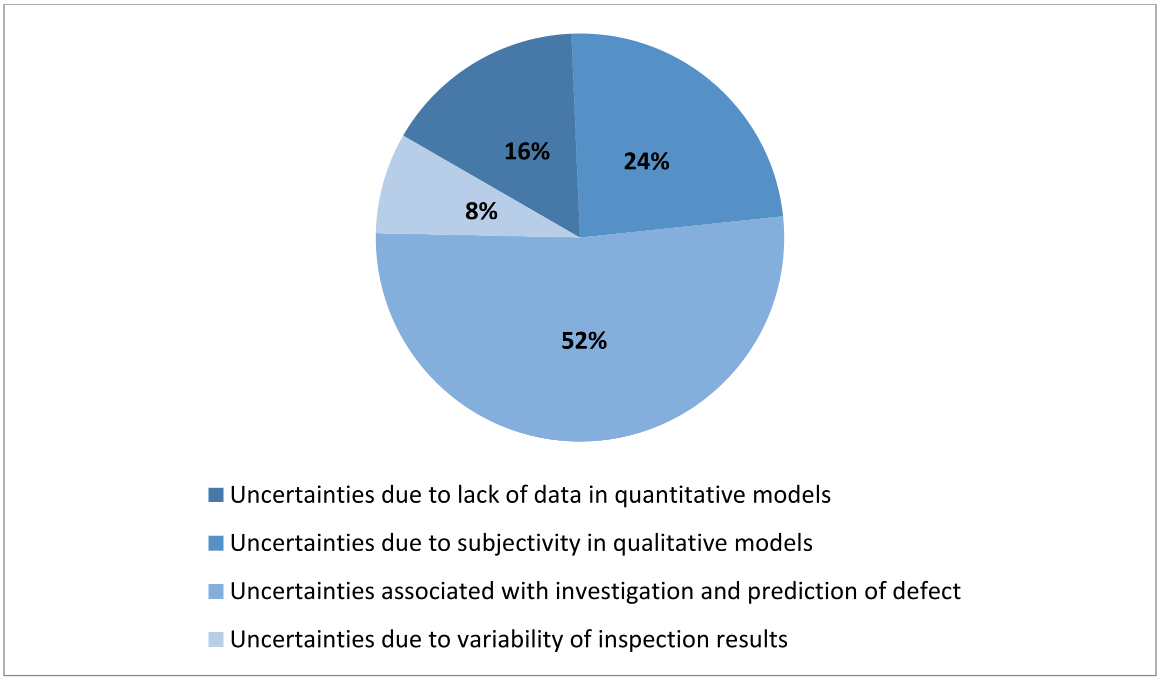


Figure 8: Distribution of 50 studies for risk-based maintenance of assets showing uncertainties influencing the effectiveness of maintenance policies decisions

Table 1: Probabilistic models for pipeline condition prediction

Reference	Model	Method
Pandey (1998)	Probabilistic analysis, Monte Carlo simulation	The pipe internal condition prediction model is applied to determine the optimal inspection interval and maintenance strategy
Ahammed (1998)	Probabilistic, A non-linear limit state model	Model is used to determining the remaining life of pressurized pipeline in the presence of active corrosion
Caleyo, Velázquez, Valor, & Hallen (2009)	Markov chain model	Markov chains are used for modelling external pitting corrosion
Papavinasam, Doiron, & Revie (2010)	Design of experiment , Statistical model	The model predicts the growth of internal pits based on the operational parameters of the field. It also considers the variation of the pitting corrosion rate as a function of time and determines the error in the prediction.
Breton, Sanchez-Gheno, Alamilla, & Alvarez-Ramirez (2010)	Bayesian probabilistic model	Probabilistic model based on Bayesian approach to determine the failure rate, risk evaluation and maintenance policies.
Pandey & Lu (2013)	Bayesian statistics based comprehensive two-stage hierarchical model	Estimation of parameters of degradation growth rate distribution from noisy degradation measurement data, and formulates the associated maximum likelihood function
Ossai, Boswell, & Davies (2015)	Probabilistic analysis, Monte Carlo simulation	To estimate the internal pit depth growth and reliability of aged oil and gas pipelines
Hui Wang, Yajima, Liang, & Castaneda (2015a)	Bayesian inferential framework	The framework assumes the actual corrosion defect depth based on detection theory and used cluster analysis to find the effect of soil property variation on external corrosion
Hui Wang, Yajima, Liang, & Castaneda, (2015b)	The combination of hidden Markov random field theory and a finite mixture model	To predict the effect of heterogeneous soil properties on external corrosion growth.
Jain et al. (2015)	Probabilistic model using Bayesian network method	Estimation of external corrosion growth on pipes for quantitative risk assessment

Table 2: Types of maintenance policies for single units and pipeline assets

Type of assets	Type of policies				
	Age-Based Policies	**Service Time Policies**	**Failure limit base policies**	**Condition based Policies**	**Risk-based policies**
Units/Plants	✓	✓	✓	✓	✓
Pipelines		✓		✓	✓

Table 3: Summary of literature on extended preventive maintenance policy models for single units

Source	Decision Criterion					Action				
	Age		Time in service	Fixed cost	No of Failure / Repair limit	Repair		Replacement/Repair		
	Fixed	Sequential				Imperfect / Minimal	Perfect	Periodic	One time	Block
(Barlow & Hunter 1960)			✓			✓		✓		
(Gardent & Nonant 1963)				✓	✓				✓	
(Makabe & Morimura 1963)					✓				✓	
(Drinkwater & Hastings 1967)				✓	✓				✓	
(Morimura 1969)			✓		✓				✓	
(Nakagawa & Osaki 1974)			✓		✓				✓	
(Tahara & Nishida 1975)	✓					✓		✓		
(Berg & Epstein 1976)	✓		✓			✓				✓
(Tango 1978)			✓			✓			✓	✓
(Bergman 1978)	✓				✓				✓	
(Park 1979)					✓	✓				
(Nakagawa 1980)			✓						✓	✓
(Nakagawa 1981b)			✓						✓	
(Nakagawa 1981a)	✓		✓					✓	✓	
(Nguyen & Murthy 1981)		✓	✓			✓			✓	
(Nguyen & Murthy 1981)					✓	✓			✓	
(Beichelt 1982)				✓	✓				✓	
(Nakagawa 1984)	✓				✓	✓			✓	
(Nakagawa 1986)			✓			✓				✓
(Lie & Chun 1986)				✓	✓					
(Nakagawa 1986)(Nakagawa 1988)		✓	✓			✓				
(Yun & Bai 1987)				✓	✓		✓		✓	
(Valdez-Flores & Feldman 1989)	✓			✓					✓	
(Yeh 1988)					✓				✓	
(Kapur et al. 1989)				✓	✓				✓	
(Stadje & Zuckerman 1990)			✓		✓				✓	
(Makiš & Jardine 1991), (Makis & Jardine 1993)					✓	✓				
(Chun 1992)			✓			✓				
(Kijima & Nakagawa 1992)		✓					✓			
(Block et al. 1993)	✓				✓				✓	
(Sheu et al. 1993) (Sheu et al. 1995)	✓					✓		✓		
(Dagpunar & Jack 1994)			✓		✓	✓				
(Liu et al. 1995) (Pham & Wang 1996)			✓			✓		✓		
(Pham & Wang 1996)	✓					✓			✓	
(Koshimae et al. 1996)			✓		✓				✓	
(Dohi et al. 1997)			✓		✓	✓			✓	
(Wang & Pham 1999).			✓		✓					✓
(Wang & Pham 1999)	✓								✓	
(Castro & Sanjuán 2008)		✓				✓				

Table 4: Summary of different types of preventive maintenance policies for single units

Preventive maintenance policies	Type of units	Decision Criteria	Actions
Aged-Based	Repairable	Predefined age or complete failure before the age	maintained preventively at predetermined ages and is replaced only at the complete failure
	Non-repairable		replaced at a predetermined age regardless of the condition
Time in Service-Based Decision Policies	Repairable	Time in service. The time interval is independent of the failure history	Imperfect maintenance till the unit replaced at complete failure.
Failure/Repair Limit Based Decision Policies	Repairable	specific (predetermined) number of failures or repairs	Replacement after fixed numbers of failure/ repair. Repairs are imperfect

Table 5: Classification of risk analysis methodologies modified after (Arunraj & Maiti, 2007)

Techniques	Methodologies		
	Probabilistic	**Deterministic**	**Probabilistic and deterministic**
Qualitative	- Delphi technique - expert judgment - rapid ranking	- Action error analysis - Checklist - Concept hazard analysis - Goal oriented failure analysis - Hazard and operatibility (HAZOP) - Human hazard operability (Human HAZOP) - Hazard identification system (HAZID) - Master logic diagram - Optimal hazard and operability (OptHAZOP) - Plant level safety analysis (PLSA) - Preliminary risk analysis - Process hazard analysis (PHA) - Reliability block diagram (RBD) - Task analysis - What if? Analysis - Sneak analysis - Risk matrix	- Maximum credible accident analysis - Safety culture hazard and operability (SCHAZOP) - Structural reliability analysis (SRA)
Semi-Quantitative	- IAEA-TECDOC-727 - Maintenance analysis - Semi-quantitative fault tree analysis - Shortcut risk assessment	- Domino effect analysis - Layers of protection analysis (LOPA) - Predictive risk index - World health organization (WHO) - Risk priority number - Failure mode effect analysis (FMEA) -	- Safety analysis - Failure mode effect criticality analysis (FMECA) - Facility risk review (FRR)
Quantitative	- Event tree analysis (ETA) - Fault tree analysis (FTA) - Petri nets - Probabilistic fault tree (PROFAT) - Fuzzy fault tree analysis - Risk integral	- Accident hazard index - Chemical runaway reaction hazard index - Dow's chemical exposure index (CEI) - Dow's fire and explosion index (FEI) - Fire and explosion damage index (FEDI) - Hazard identification and ranking (HIRA) - Instantaneous fractional annual loss (IFAL) - Reactivity risk index (RRI) - Safety weighted hazard index (SWeHI) - Toxic damage index (TDI)	- Method organised systematic analysis of risk (MOSAR) - Quantitative risk analysis (QRA) - Rapid risk analysis - Probabilistic risk analysis (PRA) - International study group on risk analysis (ISGRA) - Optimal risk assessment (ORA) - IDEF methodology

Table 6: Description of techniques used in risk analysis modified after (Arunraj & Maiti, 2007)

Risk analysis steps	**Techniques**
Hazard analysis (failure scenario development)	- Maximum credible accident scenario (MCAS) - Event tree development
Consequence estimation	- Source models - Impact intensity models - Toxic gas models - Explosions and fires models - Expert opinion
Likelihood estimation	- Fault tree analysis (FTA) - Probabilistic fault tree analysis (PROFAT) - Expert opinion - FMEA**
Risk estimation	- Fuzzy logic - Risk matrix - Simple product of probability of failure and damage loss
Risk acceptance	- Dutch acceptance criteria - ALARP (as low as reasonably possible) - USEPA acceptance criteria
Maintenance planning	- Reverse fault analysis - Analytical hierarchy process (AHP)

Table 7: Analysis of maintenance policies in the perspective of oil and gas pipelines

Policy	Assessment criteria	Decision criteria	Pros	Cons	Suitability for pipelines
Corrective maintenance policy	Complete failure	• Failure information	• Cost effective	• Long downtime	Not appropriate for the Pipelines
Preventive maintenance policy	Predefined intervals, e.g., Age, service	• Expert's opinion • Industrial historical practice • last repair	• Reduced the incidence • Cost effective • reduction in a production loss	• Decisions are very subjective, the condition of the pipeline was not assessed.	Not appropriate for the high consequences Pipelines
Predictive Maintenance / Condition-based Maintenance policy	Condition based assessment	• Inspection and condition assessment	• Real-time assessment of pipelines.	• High inspection cost. • Uncertainties of inspection process • Decisions are limited to the condition assessment • Challenges for determining the inspection intervals	Suitable for Pipelines
Proactive Maintenance / Risk Based Maintenance Policies	Risk assessment associated with condition and failure	• Inspection and condition assessment • Risk assessment • need-based maintenance strategy	• Real-time assessment of pipelines. • Decrease the probability of harmful events • Reduce the harmful consequences of the occurred events	• Uncertainties and variability in inspection data • conservative assumptions • Subjectivity of the decision-makers' opinion	Most used policy for Oil and gas pipelines

Table 8: Summary and evaluation of risk based maintenance policies for oil and gas pipelines

Uncertainties due to	Causes	Effect	Solutions	Assumptions / limitations
Lack of data in quantitative models	- Limited availability of accident data (Jo & Ahn, 2005; Jo & Crowl, 2008) - Insufficient data about population density, economy condition, pipeline operation parameters and, wall thickness (Bartenev et al., 1996)	- Increase uncertainty of the risk analysis	- (Dawotola et al., 2009) - fitting historical data of failure by homogenous Poisson process	- Corrosion assumed to be uniform process - Pipeline system will be restored as new after minimal repair - Repair will not affect the pipeline failure frequency - Homogeneity in pipeline segment
			- (Han & Weng, 2011) Grey Correlation Theory and the Reliability Engineering Theory	- Causation index inherent risk index and consequence index have the same weight and have equal contribution to the risk - Entire pipeline as a single segment - Dimensionless transformation is used to convert the original sequence of data into comparable sequence as a single segment
			- (Deng, 1989) Grey correlation theory	- Co-relation depends upon the similarity of the geometric shape of the data series curves
Subjectivity in qualitative models	- Subjectivity in expert opinion - Use of absolute risk number (API-580, 2009) - Variation in selection of failure mechanism - Variation, in conclusion, averaging of all consequences - Neglecting the impact of individual consequence - Difference in contents of inspections and inspection intervals	- vast variation in the results of the risk-based analysis (Geary, 2002), (F. Khan et al., 2004)	- (F. Khan et al., 2004) Fuzzy logic aggregative risk analysis	- Fuzziness in likelihood failure and their consequences
			- (F. I. Khan & Haddara, 2003) Fault tree and reverse fault tree analysis	- Predefined level of risk as a criterion for planning the maintenance - The risk is affected by two factors: the accuracy of the estimates of the probability of failure and the quality of the consequence study.
			- (Dawotola et al., 2012; Prasanta K Dey, 2001; Prasanta Kumar Dey et al., 2004; Prasanta Kumar Dey, 2003, 2004) - AHP multi-criteria decision tool and weighted average technique - Likelihood loop used to identify the failure factors	- The studies are more subjective to the expert opinion. No sensitivity analyses were carried out to see the effect of maintenance on the cost.
			- (Cagno et al., 2000; Cockshott, 2005; Dawotola et al., 2012; Prasanta K Dey, 2001; Prasanta Kumar Dey, 2003, 2004; Moubray & Lanthier, 1991) Fuzzy logic method (FL), Data Envelopment Analysis (DEA), Analytic Hierarchy Process (AHP), Event Tree Analysis (ETA) and Fault Tree Model (FTM)	- Focus only on the identification of the causes of the event. - Variations in a selection of failure mechanism, - Diversity in conclusions - The difference in the inspection periods.
Investigation and prediction of defect	- Uncertainties in the prediction of defect growth, - Effect of defect on the integrity of pipelines (M. Singh & Markeset, 2009)	- Risk quantification non-realistic values	- Fuzzy based model(Agarwal et al., 2004; Ayyub & Klir, 2006; Bae et al., 2004; Cheng, 2000; Ferdous et al., 2009, 2011; Huang et al., 2001; Sadiq et al., 2008; Sawyer & Rao, 1994;	- Model emphasized on mechanical failures such as quality of installation of pipeline, manufacturing pipe, quality of welding, and percentage of inclusion.

	- Multi-dimensional consequences of pipeline failure (Brito et al., 2010) - Lack of knowledge of failure mechanism - Conservative assumptions made by the experts - Linguistic expressions - Uncertainties of design and material fault, limited understanding, and vagueness of the failure mechanism (Ayyub, 1991; Ferdous et al., 2009; Sadiq et al., 2008; Sawyer & Rao, 1994; Yuhua & Datao, 2005)		Sentz & Ferson, 2002; Wilcox & Ayyub, 2003)	- Triangular fuzzy number was used to represent the fuzziness of failure probabilities
			- Fuzzy based inspection model for the corrosion rate assessment (M. Singh & Markeset, 2009)	
			- Fuzzy based bow-tie analysis - Fault tree analysis (FTA) - Event tree analysis (ETA) (Spouge & others, 1999), (Cockshott, 2005; De Dianous & Fiévez, 2006; Duijm, 2009; Markowski et al., 2009; Shahriar et al., 2012), (Yuhua & Datao, 2005)	- FTA and ETA result deals with the likelihood of an event and cannot characterise the severity of risk associated with the incident.
			- ELECTRE TRI integrating utility theory (Brito et al., 2010)	- The model assigned the risk category to each section of pipelines by considering the impact of the accident on the human, environment and economics. - Lack of sensitivity analysis to see the effect of individual risk item over system risk
Variability of inspection results (M. Singh & Markeset, 2014a, 2014b, 2014c)	- The inherent characteristics of Instrumental variability - Complexities of operating conditions. - Random nature of the variables (M. Singh & Markeset, 2014b) - Non-uniform condition of the pipeline dimensional parameters - Variation in corrosion pits location, length, and depth	- Variability in measured data	- Fuzzy probability distribution function (M. Singh & Markeset, 2014b)	- Combined the probabilistic and possibilistic approaches - Probabilistic models have a tendency to ignore the low probability situations that may cause a severe impact. - Possibilistic approach addresses with low possible events - Possibilistic approach is too subjective and gives more imprecise results
	- operator's skill - limitation of measuring instrument and their operation	- Uncertainty in measured data	- Probabilistic analysis framework (Hallen et al., 2003)	- ILI data combined with fitness-for-purpose probabilistic assessments by using structural reliability analysis (SRA)