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RISK BASED MAINTENANCE OF A CROSS-COUNTRY PETROLEUM PIPELINE SYSTEM

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ABSTRACT

This paper proposes a data-driven approach in determining an optimal inspection interval for a petroleum pipeline system. The approach accounts for the determination of both the probability of failure and its associated consequences. The probability of failure is estimated by fitting the historical data of failure of the pipeline into either a homogenous Poisson process or non-homogenous Poisson process (power law). The analysis of historical data reveals the Poisoneous form that gives better description of the failure process. The consequences of failure are calculated in terms of economic loss, environmental damage and loss of human life. Both the failure probability and consequences are utilized to estimate the total loss of an operating pipeline system. A risk based integrity maintenance optimization of the pipeline is achieved by minimizing the economic loss, while taking the human risk and maintenance budget as constraints. The proposed framework is utilized in the maintenance planning of a very long cross country petroleum pipeline system. The outcomes are robust and well validated. The framework can be applied to any engineering system that requires inspection and maintenance planning.

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INTRODUCTION

The field of maintenance management has evolved over the years from using intuitive techniques to the application of more sophisticated maintenance strategies, such as routine based maintenance, condition monitoring, and reliability centered maintenance (Khan and Haddara 2004). The maintenance of production systems based on intuition, using the so called break-and fix approach, is largely considered crude and unacceptable under present safety criteria (Thoft-Christensen and Sørensen 1987). In a further development, the high costs associated with the maintenance of petroleum assets require the development of systematic and effective maintenance approaches. A well rounded asset maintenance strategy will ensure system reliability and reduced life cycle cost (Arunraj and Maiti 2006). In reality, maintenance resources are usually limited, and require effective allocation of maintenance budgets without compromising on public safety. This explains why there has been a growing awareness on integrity maintenance in both the industry and the academia.

In a broader sense, maintenance activities can be classified into two main categories, namely corrective maintenance and preventive maintenance. The major difference between the two categories is that corrective maintenance is carried out after the failure of the equipment, while preventive maintenance is performed during the operation of the equipment. For practical applications, risk-based maintenance optimization strategy can be formulated with the purpose of combining the requirements of asset maintenance with risk compliance and acceptability. Based on risk-based preventive maintenance approach, the asset manager can ensure that appropriate testing and inspection are carried out at regular intervals without compromising public safety.

Transportation and storage assets used in the production of oil and gas include the floating production, storage and offloading units (FPSOs), mobile offloading production units (MOPUs), tension leg platforms, production semi-submersibles, jack-ups, pipelines, etc. The main production objective for these assets is to ensure that

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systems function without hindrance, and fully comply with appropriate safety standards. Generally, for such systems, it is often difficult to quantify the benefits of maintenance because standards are set by the authorities to define acceptable failure rates.

The costs of maintenance are normally optimized in order to comply with minimum required safety standards. Different approaches to maintenance optimization have been proposed by different authors, ranging from simplified analytical methods (Vatn et al. 1996), to advanced mathematical models (Dekker et al. 1994; Tsai et al. 2001). Unfortunately, most of the advanced maintenance models available in academic literatures are often too laborious, and difficult to apply in real applications that they are meant to serve. Dekker (1996) claimed that the field of maintenance optimization has one of the widest gap between theory and applications, and Scarf (1997) emphasized the need for maintenance modelers to collaborate with practice engineers for academic maintenance optimization models to have any real practical applications.

One promising maintenance optimization technique is the use-based maintenance model presented in Git (1992) and in Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek, i.e., Netherlands Organization for Applied Scientific Research (TNO) (2005). In the model, total cost due to operation and failure of a production system is minimized so as to achieve an optimum maintenance interval for preventive maintenance of repairable systems (Taghipour et al. 2010). In addition, the benefit to cost (B/C) ratio interval derived from performing preventive maintenance can be maximized to achieve an optimum. The minimization and maximization of the total cost function and the B/C ratio, respectively appears to be very promising, especially in finding the optimum maintenance interval for a production system, considering the preventive maintenance policy.

The methodology proposed in this work consists of risk estimation, maintenance strategy selection, and

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maintenance optimization. Risk is defined as a combination of probability of failure and its anticipated consequences. The statistical approach to reliability of repairable systems is utilized to determine the failure rate of the system based on historical records of failure. Maintenance optimization decisions for each component of the system is made based on the level of risk reduction obtained from implementing maintenance strategies. As opposed to most current methods of reliability centered maintenance, the proposed framework is based on real data, thus ensuring robustness in the optimization process. Furthermore, with enhanced accuracy in risk assessment due to the use of real data, considerable cost savings in the inspection and maintenance planning may be achieved.

The proposed methodology is utilized to formulate the risk-based maintenance strategy for a cross country petroleum pipeline system. A use-based preventive maintenance plan is proposed to calculate the optimal maintenance interval for segments of the pipeline, while satisfying the constraints of cost and risk minimization. The paper is organized as follows. In the next section, maintenance optimization models are briefly reviewed. Afterwards, the proposed risk-based maintenance optimization approach is introduced and the steps that are involved in the optimization process are briefly discussed. Then the use-based maintenance strategy is discussed, and the total cost function and the optimization equation for a system are developed. An example of corrosion failure of a petroleum pipeline system is used to show how the proposed optimization framework can be utilized to formulate inspection and maintenance strategies for an operating pipeline. Lastly, the section on conclusion discusses the results obtained and the conclusions that can be derived from the results.

MAINTENANCE OPTIMIZATION MODELS

Maintenance optimization models are mathematical models developed to determine the optimum balance between the costs and benefits of maintenance and the time to execute maintenance activities, while taking appropriate constraints into account. Dekker (1996) expressed that maintenance optimization generally entails four aspects, namely: (i) description of a technical system to be optimized, (ii) modeling of the real-time deterioration of the system, and its associated consequences, (iii) description of available information about the system and the actions open to management, and (iv) development of an objective function and a suitable optimization technique for the function. These steps are similar to the four steps presented in the utility approach proposed by Vatn et al. (1996). The four steps entail problem definition, loss function description, dependability modeling, and result compilation.

The conventional optimal maintenance approach involves fixing the interval that minimizes the *total expected cost* for a planning period (Barbera et al. 1996; Castanier and Rausand 2006). The relationship between the costs and maintenance interval (τ) under this assumption is displayed in Fig. 1.

In general, three types of maintenance models can be identified based on the failure behavior and whether the model allows condition monitoring by inspection. The three models are condition-based model, failure-based model, and use-based model (Git 1992). The *condition-based model* optimizes the inspection interval of a component and predicts when a maintenance action should be initiated, once a specified condition is attained. The *failure-based model* results in corrective maintenance only and it is used to predict maintenance action after the failure of a component. The *use-based model* is designed to optimize the maintenance interval of a production system. Similar to the condition-based maintenance, the use-based maintenance also results in both preventive and corrective maintenance.

The proposed framework in this paper adopts the use-based maintenance model because it is particularly suitable for repairable systems, and particularly for components whose failures are noticeable.

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THE PROPOSED RISK-BASED MAINTENANCE STRATEGY

Risk based maintenance methodology involves the inclusion of risk aspect into maintenance. In the methodology, a maintenance approach is selected, and then included into a risk-based decision framework to achieve the optimum risk-based maintenance.

Optimization Framework

The basic methodology and the building blocks of the optimization approach for a pipeline system is depicted in Fig. 2. The approach presented here involves the use of historical data to obtain direct estimates of the probability and consequences of failure, which would allow risk calculation and maintenance optimization. It is based on the optimization of the total cost of failure subject to acceptable environmental and human safety risks, with more emphasis on minimization of risks to human safety.

Optimization Procedures

The Optimization process inherent in the framework consists of the following six steps: (i) probability of failure estimation, (ii) determination of consequences of failure, (iii) estimation of risk of failure, (iv) calculation of risk reduction, (v) calculation of total cost function, and (vi) determination of cost-optimal inspection frequency of the pipeline in a preventive maintenance policy.

Probability of Failure Estimation

The objective of this step is to establish a stochastic model that can be used to determine the probability of failure. In achieving this, the pipeline system is divided into different segments based on a set of attributes. For each segment, typical failure mechanisms were identified. Typical failure mechanisms for pipeline ruptures include corrosion, third party damage, operational errors, structural defects, and minor failures. Each failure mechanism can be further divided into different categories, as appropriate. For example, corrosion failures can be grouped into pitting corrosion, uniform corrosion, stress corrosion cracking, etc. (Freeman 2002).

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The probability of pipeline failure can be computed in many ways. This paper in particular adopts the statistical approach to the reliability of repairable systems (Rigdon and Basu 2000; Caleyo et al. 2008). The approach assumes that pipelines are repairable systems; whose reliability can be estimated based on historical damage records. The historical records of failure for each segment is obtained and fitted to either *homogenous Poisson process (HPP)* or *non-homogenous Poisson process (NHPP)*, otherwise called the *power law process*. The aim of this procedure is to determine the stochastic distribution of equipment failure and estimate the rate of failure. The statistical approach is data-driven, and may not be suited for equipment with insufficient failure data. If adequate failure data are lacking, decision models such as analytical hierarchical process (AHP), utility theory or expert judgment can be considered. If AHP is utilized, it is advisable to augment this methodology with structured expert judgment to reduce subjectivity, as discussed in Dawotola et al. (2010).

Consequences of Failure

In this step, the likely consequences of potential hazards are estimated by determining the impacts of failures on human lives, the environment and economic profit. These three consequence components can be combined into a single measure of loss, and utilized to estimate the total loss of failure due to a given hazard.

The failure of corroded petroleum pipeline may lead to oil spills or fires/explosions, or even a combination of both. Shebeko (2007) analyzed the hazardous factors typical for accidents with fires and explosions on oil storages, which range from thermal radiation at pool fires and torch fires, thermal action of combustion of vapour clouds at a lash-fire, overpressure at combustion of vapor clouds, and high temperature of air, smoke and toxic combustion products with low oxygen concentration.

The estimate of consequences of pipeline explosion involves rigorous and extensive mathematical computation. Palazzi et al. (2004) for example, explained that the evolvement of hydrocarbon spills can be described

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according to three different time-evolution scenarios, namely instantaneous, continuous and semi-continuous. Each scenario requires different sets of complicated mathematical formulae to model the consequences of the spills, hence the need for modeling tools. Many commercial software have been developed for estimating hazardous consequences in transportation systems. They include: PHAST FX, RISKAT, WHAZAN, and SAFETI, etc. (Dziubinski et al. 2006; Mannan 2005).

Total Risk

The risk of failure for each failure mechanism is estimated based on the results of failure probability and consequence analysis, as earlier described. The level of risk calculated thus signifies the *total risk* for the system. Total risk is estimated by summing the environmental, economic and human safety (individual and societal) risks for each hazard cause and failure mode. Future risks can be determined by applying a discount factor to the present value of the expected total risk over the first period. The total risk over an infinite time horizon would become: R/r, in which R is the expected total risk over the first period and r is the discount factor due to economic growth net of inflation. The computed risk will then be evaluated against *acceptable risk* to determine its compliance with the stipulated regulations.

Setting up acceptable risk criteria depends on a number of factors which include the criticality of the system, the requirements of the local safety authority responsible for maintaining the safety of critical infrastructures, and the level of risk that individuals located within the facilities are willing to accept based on their personal cost-benefit analysis. Any pipeline segment with risks exceeding the acceptable criteria will be re-evaluated after suitable maintenance plans have been proposed. The *risk reduction* due to maintenance effect will also be considered and evaluated.

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Risk Reduction

This step entails the calculation of the amount of reduction in the failure rate for each pipeline segment after integrity maintenance has been carried out. The *failure rate reduction* is utilized to estimate cost savings due to risk reduction. This is a vital step in the maintenance optimization loop, as it justifies the whole optimization process. If the level of risk reduction falls below expectation, it implies that the proposed maintenance plan is not effective enough in mitigating the failure rate. In this case, a more suitable inspection and maintenance strategy has to be considered.

USE-BASED MAINTENANCE MODEL

There are many criteria that can be defined in a maintenance optimization problem. These criteria include optimization of reliability function, minimizing downtime, minimizing production loss, quality loss and expected total costs per unit time. These criteria are defined based on a number of variables, including the type of production systems, the production philosophy and the level of demand of the product (Chareonsuk et al. 1997). The maintenance optimization proposed in this paper involves the combination of two criteria; minimizing the *expected total cost* and maximizing the *benefit-to-cost ratio*. The *expected total cost* is applied to achieve a robust risk assessment while the B/C ratio is used if global optimum cannot be achieved from minimizing the *expected total cost*. A major benefit of this approach is that it measures risk as a cost spread over time. Total cost approach can be challenging, especially due to the challenge of measuring potential safety loss in monetary terms. This is very controversial and somewhat political. Nevertheless, several benefits of the approach have been demonstrated in Restrepo et al. (2009), for instance.

Estimation of Expected Total Cost Function

The *expected total cost* function $E[C \mid \tau]$ defines the total cost, C of preventing failure of an operating system at a given maintenance cycle, τ. The model optimizes the maintenance interval and searches for a balance

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between preventive and corrective maintenance costs based on the time-based failure behavior of the pipeline.

For a single maintenance cycle, τ it is mathematically computed as:

$$E[C \mid \tau] = C_r * P\{t \mid \tau\} + C_p * [1 - P\{t \mid \tau\}] \tag{1}$$

Where C_r and C_p are corrective maintenance and preventive maintenance costs respectively. The corrective maintenance cost consists of replacement cost, downtime cost and consequences of failure (damage cost). The preventive cost, on the other hand, is obtained from inspection cost and downtime cost. It is expected that the downtime cost due to preventive maintenance cost will be less than or at most equal to downtime cost due to corrective maintenance cost.

The term $P\{t \mid \tau\}$ is the conditional probability that the system survives failure at a given time *t*, given that it did not fail until τ. The reliability function is described by $R(t) = 1 - P\{t \mid \tau\}$.

The *mean time before failure* (MTBF) can be obtained from $R(t)$ or vice-versa by solving:

$$MTBF = \int_0^\infty R(t)dt \tag{2}$$

Similarly, the expected length of maintenance cycle $E(\tau)$ is given as:

$$E(\tau) = \int_0^\tau R(t)dt \tag{3}$$

The *cost per unit time* (Q), otherwise known as the *asymptotic cost rate* in a renewal cycle, is the ratio of the expected total cost to the expected length of renewal cycle. It is given by van der Weide (2010) as:

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$$Q = \frac{E[C|\tau]}{E(\tau)} = \frac{C_r * P\{t \mid \tau\} + C_p * [1 - P\{t \mid \tau\}}{\int_0^\tau R(t)dt} \quad (4)$$

$P\{t \mid \tau\}$ which is the conditional probability described earlier can be further expressed as:

$$P\{t \mid \tau\} = \frac{P[t+\tau]}{P[\tau]} \quad (5)$$

Using $T = t + \tau$, for the interval from t to T equation (1) becomes:

$$E[C \mid \tau] = C_r\left[\frac{P(T)}{P(\tau)}\right] + C_p\left[1 - \frac{P(T)}{P(\tau)}\right] \quad (6)$$

Equation (6) is the equation for maintenance cost of the pipeline during the interval τ to T. Assuming that the service life of the pipeline is $\overline{T}$, then the above expression for the *expected total cost* can be generalized into:

$$E[C \mid \tau] = \frac{\overline{T}}{\tau}\left[C_r P(T) + C_p\{1 - P(T)\}\right] \quad (7)$$

Substituting for $R(T)$, the equation becomes:

$$E[C \mid \tau] = \frac{\overline{T}}{\tau}\left[C_r P(T) + C_p R(T)\right] \quad (8)$$

The failure rate of any failures that can be described by a homogenous Poisson process has a constant value (λ). In addition, its failure distribution function and reliability function are given as: $P(T) = 1 - e^{-\lambda t}$ and $R(T) = e^{-\lambda t}$ respectively.

The expressions for $P(T)$ and $R(T)$ can be substituted into equation (8) to obtain $E[C \mid \tau\}$ for the homogenous

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Poisson process case.

Similarly, for Power law model, the failure distribution function at any given time, *t* is given by:

$$P(T) = \lambda(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1},\ t > 0 \tag{9}$$

Where, the parameters of β and θ are the shape and scale parameters of the failure intensity function, respectively. The intensity function decreases, if $\beta < 1$, and increases if $\beta > 1$. If $\beta = 1$, then the power law process reduces to a homogenous Poisson process with intensity function: $\lambda(t) = 1/\theta$. If $\lambda(t)$ is decreasing, then the system is improving.

The maximum likelihood estimates (MLE) of β and θ, for a time truncated data having N number of failures is given as:

$$\hat{\beta} = \frac{N}{\sum_{i=1}^{N} \log(t/t_i)} \tag{10}$$

and

$$\hat{\theta} = \frac{t}{N^{1/\hat{\beta}}} \tag{11}$$

Where N = number of failures recorded before failure was truncated at time, t

Similarly, the reliability function for the Power law process is given as:

$$R(T) = \exp\left[-\left(\frac{t}{\theta}\right)^{\beta}\right] \tag{12}$$

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Equation (9) and (12) is substituted into equation (8) to obtain the final expression for $E[C\,|\,\tau\}$ under the power law case.

The optimum maintenance interval τ is the time that minimizes equation (8). It is obtained by solving for τ that satisfies this equation.

Benefit to Cost-Ratio Function

There are instances whereby minimizing the *expected total cost* would not necessarily lead to optimality. In such cases, maintenance optimization can be extended to include maximization of the benefit derived from risk reduction (Jiang 2006; Natti 2008).

The benefit derived from periodic preventive maintenance, $B(\tau)$ can be defined as the product of the average difference in the reliability of the equipment with and without maintenance and the incidence cost, C_{inc} (Lappa et al. 2006; Ghosh and Roy 2009). The expression for $B(\tau)$ is stated as:

$$B(\tau) = C_{inc}\left[\frac{1}{\lambda\overline{T}}\left\{\frac{e^{-\lambda\overline{T}}-1}{1-e^{\lambda\tau}}+\frac{e^{-\lambda\overline{T}}-1}{1-e^{-\lambda\tau}}\right\}+\frac{1-e^{-\lambda\tau}}{\lambda\tau}\right] \qquad (13)$$

Where λ is the equipment failure rate.

The B/C ratio due to maintenance activity is defined as:

$$B/C\ ratio = \frac{B(\tau)}{E[C|\tau]} \qquad (14)$$

It can be maximized to achieve optimum maintenance in the case of constant failure rate.

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Optimum Maintenance Interval

The optimum maintenance interval of inspection and repair is evaluated by minimizing the value of the *expected total cost*, derived in Eq. 8. That is, solving for τ that satisfies the equation, and that will give the most profitable preventive maintenance structure for the system.

For a risk-based maintenance optimization, constraints for the optimization equation are set by imposing a limit on Individual risk, $IR_{x,y}$ and maintenance budget, C as appropriate.

Optimization objective is therefore defined as: Minimize *expected total cost*, $E[C \mid \tau]$

Subject to:

$IR_{x,y} \leq R_t$ (Risk criterion)

$C \leq C_t$ (Maintenance budget)

Where R_t is maximum acceptable risk to life (*t* stands for target) and C_t is the maximum maintenance budget of the company.

To determine acceptability of risk, two points of view are considered. First is the point of view of the individual who decides to undertake a risky activity, having pre-knowledge of the consequences of such activities and weighing it with direct and indirect benefits derived from its performance. Second, is the perspective of the society, in which an activity is judged acceptable, based on the risk-benefit trade-off for the total population.

The individually acceptable level of risk is given by Vrijling et al. (1998) as:

$$IR = P_{fi} P_{d|fi} < \beta_i * 10^{-4}. \quad (15)$$

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Where, P_{fi} is the probability of death per year, $P_{d|fi}$ is the probability of decease in the event of an accident. β_i is the policy factor, whose value varies with the degree of voluntariness with which an activity i is undertaken and with the benefit perceived.

The value of β_i depends on the level of risk an individual is willing to take, irrespective of the nationality. It range from 0.01 (for non-voluntary activities) to 100 (completely voluntary activities). Installations such as cross-country pipelines are considered involuntary and possess no direct benefit; hence a β_i value of 0.01 is selected. Therefore, equation (15) for petroleum pipelines becomes:

$$IR = P_{fi} P_{d|fi} < 10^{-6} \qquad (16)$$

Eq. 16 implies that the maximum acceptable risk value for petroleum pipelines can be set at 1E-06 per year.

The societal risk can be modeled by the frequency of exceedance curve of the number of deaths (the FN-curve) due to a specified hazard, if the specified level of harm is limited to loss of life. The acceptable societal risk criterion can be defined as:

$$E(N) + k.\sigma(N) < \beta_i.F_N \qquad (17)$$

Where $E(N)$ and $\sigma(N)$ are the expectation and standard deviation of the total number of deaths per year, respectively, k is a risk aversion factor, and F_N is a country specific multiplication factor. The value of F_N is based on the minimum death rate of the population, the ratio of non-voluntary accident rate excluding diseases to the minimum death rate, the number of hazardous activities in the country (over an average of 20 sectors) and the population size of the country.

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Vrijling et al. (1998) tested the norm with *k*=3 for several activities in the Netherlands and found a support for the model for risk aversion index within the broad range of policy factors: $0.01 < \beta_i < 100$ and $F_N = 100$. MaiVan (2010), also made similar attempts for *k=1, 2 and* 3 and achieve different policy factors ranging from 3 to 7.5 for Vietnam.

The maximum individual and societal risks can be input into the optimization equation. However, it should be noted that these values are valid only if the habitation around the pipeline (for which the risk calculated was based) remains unchanged.

RISK-BASED MAINTENANCE OPTIMIZATION OF A PIPELINE SYSTEM

The proposed risk-based maintenance strategy is applied to a twenty year old crude oil pipeline system located in southern part of Nigeria, West Africa. The pipeline system is divided into three unique segments based on their unique physical characteristics and process conditions. Corrosion history from 1999 to 2009 for the pipeline system was collected and recorded for each segment. Basic features of the pipelines are summarized in Table 1 below. The pipeline segments are assumed to follow minimal repair models, and trend test is applied to test whether HPP or NHPP is a suitable model to describe the failure records.

The major failure criteria for the pipeline are corrosion, third-party damage, operational errors and structural defects. The risk values were calculated for each segment of the pipeline system and for each failure mode.

Maintenance Optimization of Pipeline Segments – Corrosion Failure Analysis

The corrosion failure history of pipeline segments PPL 1, PPL 2 and PPL 3 was collected and sub-divided into uniform corrosion, pitting corrosion and stress corrosion cracking. Failure data are based on leak incidences.

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To analyse for ruptures, the hole distribution of 88% for leak and 12% for ruptures proposed by Health and Safety Executive, HSE (1999) can be used. The statistical analysis failed to reject the null hypothesis that HPP is sufficient to describe the historical corrosion failures due to stress corrosion cracking. It was also observed from the analysis that the corrosion history of PPL 2 and PPL 3 exhibited the same stochastic behaviour in all cases.

The calculated failure rates due to all types of corrosion for PPL 1, PPL 2 and PPL 3 are 2.93E-03 per kmyr, 0.79E-03 per kmyr and 2.18E-03 per kmyr, respectively. The complete table of corrosion failure analysis for the whole pipeline system is shown in table 2. The values obtained are comparable with results obtained elsewhere for petroleum pipelines. Little (1999) reported a value of 0.85E-03 per kmyr for corrosion failure in Western Europe petroleum pipelines, 0.60E-03 per kmyr for United Kingdom cross country oil pipelines, and 0.53E-03 per kmyr for total failure of United States of America's Department of Transportation (DOT) liquid pipelines which translates to approximately 1.06E-04 per kmyr if corrosion failure is taken as 20% of general failure). The difference obtained could be due to the difference in location, physical and process properties of the pipelines. All of these attributes have been shown to have significant influence on the frequency of failure of pipelines (Restrepo et al. 2009).

Individual risk resulting from leak incidences in the pipeline system is obtained from PHAST FX 6.5.1 software. The values obtained range from 1E-05 to 1E-09 *per year* for the entire pipeline system.

Optimum Maintenance Interval

A maintenance cost model is developed based on historical cost information for all the pipeline segments. The model parameters used for the analysis are obtained from Table 2. The optimization point is achieved by minimizing expected total cost function, $E[C \mid \tau]$ given in Eq. 8 .

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Particularly for PPL 1, results on the maintenance optimization subjected to uniform corrosion with the use of power law distribution and *expected total cost* function model are given in Fig. 3. It could be observed from the figure that an optimum point (maintenance interval) lies at 1.25 yr which corresponds to an investment of $0.45 million per maintenance cycle for the segment. For the case of pitting corrosions (Fig. 4) which was governed by the HPP, no optimum period (yr) was observed when using the same *expected total cost* function model. Because of this limitation, the B/C ratio model, Eq. 14 was applied to the HPP model instead.

Using a direct enumeration, the result is an optimum maintenance interval of 1.21 yr with a B/C ratio of 1.44; corresponding to $2.30 million investment per maintenance cycle for pitting corrosions (Fig. 5), and maintenance interval of 1.95 yr, B/C ratio of 3.47, and $1.21 million investment per maintenance cycle for stress corrosion cracking (Fig. 6). Similar procedures can also be carried out for PPL 2 and PPL 3 under varying types of corrosion failures.

Sensitivity Analysis of Parameters

One of the benefits of risk based optimization of pipeline integrity maintenance is the potential for risk reduction. For an optimum maintenance, the amount of risk reduction achieved can be estimated based on the effect of maintenance activity on the probability of failure. In essence, quantifying risk reduction will be a valuable tool in evaluating the economic viability of proposed maintenance strategies.

A sensitivity analysis on preventive maintenance cost is carried out in order to estimate the optimum replacement time and risk reduction (in terms of expected cost). Table 3 shows the sensitivity analysis results due to uniform corrosion, pitting corrosion and stress corrosion cracking of pipeline segment (PPL 1). The initial optimum is indicated in italics.

The sensitivity analysis reveals that for uniform corrosion (described by NHPP) an increase in the preventive maintenance cost would lead to a corresponding increase in the maintenance cycle in other to maintain the

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posted ahead of print July 16, 2012. doi:10.1061/(ASCE)PS.1949-1204.0000121

optimum point. The increase in the maintenance cycle would result in an increase in the level of risk. However, the observation for pitting corrosion and stress corrosion cracking (described by HPP) is somewhat different. In this case, an increase in the preventive maintenance cost would lead to a corresponding increase in the maintenance cycle. However, it was observed that B/C ratio reduces when preventive maintenance cost increases. Thus the target for integrity maintenance under the HPP scenario will be to maximize both risk reduction and the B/C ratio.

It should be noted that actual decisions are dynamic and sequential; therefore, optimal maintenance interval will be expected to change over time as more information is available for the pipeline. As shown in Fig. 2, failure frequency for example, will be updated constantly as more failure data become available for the pipeline segments. When updated data for failure frequency becomes available, potential risks are calculated and actual decisions are made on whether to carry out preventive or corrective maintenance. Previous experience on the performance of different maintenance actions will be a pointer to its suitability for future maintenance policy.

CONCLUSIONS

This paper attempts to model production loss of a cross-country petroleum pipeline under pitting corrosion, uniform corrosion and stress corrosion cracking using available data. The proposed framework is utilized to determine the risks of failure and the optimum maintenance interval for the pipeline. The framework combines the use-based maintenance model, where the failure rate changes with time following a non-homogenous Poisson process, with a B/C ratio model that accounts for a constant failure rate (homogenous Poisson process). Individual Risk obtained for corrosion failure for the pipeline range from 1E-05 per year to 1E-09 per year based on where the individual is located within the hazardous zone. Risk based integrity maintenance is proposed for the pipeline segments or pipeline installation that falls within the zone with individual risk greater than the minimum acceptable risk of 1E-06 per year, recommended in Eq. 16.

Journal of Pipeline Systems Engineering and Practice. Submitted September 2, 2011; accepted July 13, 2012;
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The study reveals that for crude pipelines, a homogenous Poisson process is generally adequate to model failure due to stress corrosion cracking while pitting and uniform corrosion can be fitted to either a NHPP or HPP, based on the characteristics of the pipeline segment under consideration. Based on the outcome, it can be said that minimizing the expected total cost of production systems will not always lead to global optimization, especially for systems with constant failure rates. In such situation, a good alternative will be maximizing the *benefit to cost ratio*.

It is assumed in the risk-based maintenance model that pipelines follow minimal repair in the sense that the system can be restored to as good as new condition after repair, and by extension that the pipeline's failure frequency is not altered after performing minimal repair. The limited maintenance records available for one of the pipeline segments (PPL 1) actually confirm this assumption. In particular for pipeline segment PPL 1, no considerable surge in failure occurrence was observed over time after preventive maintenance. However, more data will be required to fully establish this notion. In addition, future research would study how failure in one segment impacts the failure frequency of other segments and the entire pipeline.

The existing model does not dynamically capture changes in maintenance history, as it relates to its impact on failure frequency reduction. This is limitation and an area of future improvement in the model. The impact of maintenance on different pipeline segments, and how it translates to the entire pipeline will be worth investigating in the model. Also, the existing model assumes homogeneity of pipeline segments. Based on this assumption, pipeline segments are grouped according to pipeline properties, such as the physical and process conditions and year of installation. However, the assumption of homogeneity may not be entirely accurate and future research will need to take into account how to minimize assumption of homogeneity. One suggestion will be to have further divisions based on the similarity of maintenance history.

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REFERENCES

Arunraj, N.S and Maiti, J (2006). "Risk-Based Maintenance - Techniques and Applications". *Journal of Hazardous Materials,* vol. 142, pp. 653–661.

Barbera, F, Schneider, H and Kelle, P (1996). "A Condition Based Maintenance Model with Exponential Failures and Fixed Inspection Intervals", *Journal of the Operational Research Society*, 47, pp. 1037-1045.

Caleyo, F. Alfonso, L, Alcantara, J and Hallen, J.M (2008). "On the Estimation of Failure Rates of Multiple Pipeline Systems", *Journal of Pressure Vessel Technology*, vol. 130, no.2, pp. 021704-1 to 8.

Castanier B and Rausand, M (2006). "Maintenance Optimization for Subsea Oil Pipelines", *International Journal of Pressure Vessels and Piping*, vol. 83, pp. 236-243.

Chareonsuk, C, Nagarur, N and Tabucanon, M.T (1997). "A Multicriteria Approach to the Selection of Preventive Maintenance Intervals", *International Journal of Production Economics*, vol. 49, no.1, pp. 55-64.

Dawotola, A.W, van Gelder, P.H.A.J.M and Vrijling, J.K (2010) "Multicriteria Decision Analysis Framework for risk management of oil and gas pipelines". In: Reliability, Risk and Safety – Ale, Papazoglou & Zio (eds), pp. 307-314

Dekker, R, Smit, A and van Rijn, C (1994). *Mathematical Models for the Optimization of Maintenance and Their Application in Practice*. Maintenance Journal, vol. 9, pp.22- 26

Dekker, R (1996). "Applications of Maintenance Optimization Models: A review and Analysis", *Reliability Engineering and System Safety*, vol. 51, no. 3, pp. 229-240.

Dziubinski, M. Fratczak, M and Markowski, A.S (2006). "Aspects of Risk Analysis Associated with Major Failures of Fuel Pipelines", *Journal of Loss Prevention in the Process Industries*, vol. 19, pp. 399-408.

Freeman, S.R (2002). *Corrosion-Related Failures in: Becker, W T and Shipley, R J (eds*.), ASM Handbook, Vol. 11, Failure Analysis and Prevention, USA.

Ghosh, D and Roy, S (2009). "Maintenance Optimization Using Probabilistic Cost-Benefit Analysis", *Journal of Loss Prevention in the Process Industries*, vol. 22, no. 4, pp. 403-407.

Git, C.W (1992). "Design of Maintenance Concept", *International Journal of Production Economics*, vol. 24, pp. 217-226.

Health and Safety Executive, HSE. (1999) Assessing the risk from gasoline pipelines in the United Kingdom based on a review of historical experience, *Contract Research Report, 210/1999*, prepared by WS Atkins Safety & Reliability.

Jiang, Y, Zhang, Z, McCalley, J.D and van Voorhis, T (2006). "Risk-Based Maintenance Optimization for Transmission Equipment", *IEEE Trans Power System*, vol. 21, no. 3, pp. 1191–1200.

Khan, F.I. and Haddara, M.R. (2004). "Risk-Based Maintenance of Ethylene Oxide Production Facilities". *Journal of Hazardous Material.* A108, pp. 147-159.

Lapa, C.M.F, Pereira, C.M.N.A,Barros, M.P, (2006). "A model for preventive maintenance planning by genetic algorithms based in cost and reliability", *Reliability Engineering and System Safety*, vol. 91, no.2, pp. 233–240

Little, A.D (1999). "Risks from Gasoline Pipelines in the UK", Health and Safety Executive, UK.

Mai Van C. (2010). Probabilistic Design of Coastal Flood Defences in Vietnam, PhD Thesis, Delft University of Technology.

Mannan, S. (2005). Lee's loss prevention in the process industries: Hazard Idnetification, Assessment and Control. Vol.1 3rd edition. Elsevier, UK.

Natti, S (2008). Risk Based Maintenance Optimization Using Probabilistic Maintenance Quantification Modes of Circuit Breaker, PhD Thesis, Texas A&M University, USA.

Palazzi, E, Curro, F and Fabiano, B (2004). "Simplified Modelling for Risk Assessment of Hydrocarbon Spills in Port Area", *Trans IChemE, Part B, Proc. Safety and Environmental Protection*, vol. 82, no.B6, pp. 412-420.

Restrepo, C, Simonoff, C.J and Zimmerman, R (2009). "Causes, Cost Consequences, and Risk Implications of Accidents in U.S. Hazardous Liquid Pipeline Infrastructure", *International Journal of Critical Infrastructure Protection*, vol. 2, pp. 38-50.

Rigdon, S.E and Basu, A.P (2000). Statistical Methods for the Reliability of Repairable Systems. Wiley, New York, USA.

Scarf, P.A (1997). "On the Application of Mathematical Models in Maintenance", *European Journal of Operational Research*, Vol. 99, pp. 493-506.

Shebeko, Y.N (2007). "Fire and Explosion risk Assessment for Large-Scale Oil Export Terminal", *Journal of Loss Prevention in Process Industries*, vol. 20, pp. 651-658.

Taghipour, S, Banjevic D Jardine, A.K.S (2010) "Periodic Inspection Optimization Model for a Complex Repairable System", *Reliability Engineering and System Safety*, vol. 95, pp. 944-952.

Thoft-Christensen, P and Sørensen, J.D. (1987). "Optimal Strategy for Inspection and Repair of Structural Systems". *Civil Engineering and Environmental Systems,* vol., no. 2, pp. 94-100.

TNO (2005), Methods for Determining Probabilities, *TNO*, the Netherlands.

Tsai, Y.T, Wang, K.S and Teng, H.Y (2001). "Optimizing Preventive Maintenance for Mechanical Components Using Genetic Algorithms"*, Reliability Engineering and System Safety*, vol. 74, no. 1, pp. 89-97.

van der Weide, J.A.M, Pandey, M.D and van Noortwijk, J.M (2010). "Discounted cost model for condition-based maintenance optimization", *Reliability Engineering and system safety*, Vol. 95, Iss 3, pp 236-246.

Journal of Pipeline Systems Engineering and Practice. Submitted September 2, 2011; accepted July 13, 2012; posted ahead of print July 16, 2012. doi:10.1061/(ASCE)PS.1949-1204.0000121

Vatn, J, Hokstad, P and Bodsberg (1996), L. "An Overall Model for Maintenance Optimization*". Reliability Engineering and System Safety*, vol. 51, pp. 241-257.

Vrijling, J.K, van Hengel, W and Houben, R.J (1998). "Acceptable Risk as a Basis for Design", *Reliability Engineering and System Safety*, vol. 59, pp. 141-150

Vrijling, J.K, van Gelder P.H.A.J.M and Ouwerkerk, S.J (2005). "Criteria for Acceptable Risk in the Netherlands*", Infrastructure Risk Management Processes: Natural, Accidental and Deliberate Hazards*

Journal of Pipeline Systems Engineering and Practice. Submitted September 2, 2011; accepted July 13, 2012; posted ahead of print July 16, 2012. doi:10.1061/(ASCE)PS.1949-1204.0000121

List of Figures

Figure 1

Journal of Pipeline Systems Engineering and Practice. Submitted September 2, 2011; accepted July 13, 2012; posted ahead of print July 16, 2012. doi:10.1061/(ASCE)PS.1949-1204.0000121

Figure 1: Contributions of preventive maintenance and corrective maintenance on the maintenance interval.

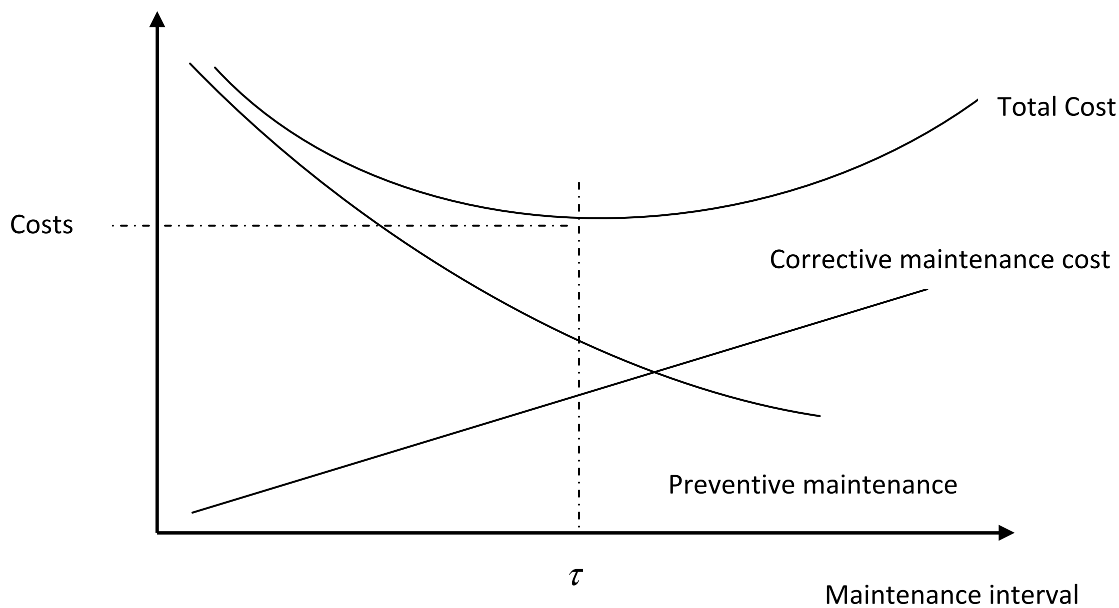

Figure 2

Journal of Pipeline Systems Engineering and Practice. Submitted September 2, 2011; accepted July 13, 2012; posted ahead of print July 16, 2012. doi:10.1061/(ASCE)PS.1949-1204.0000121

Figure 2: Maintenance Optimization Framework for a Pipeline system

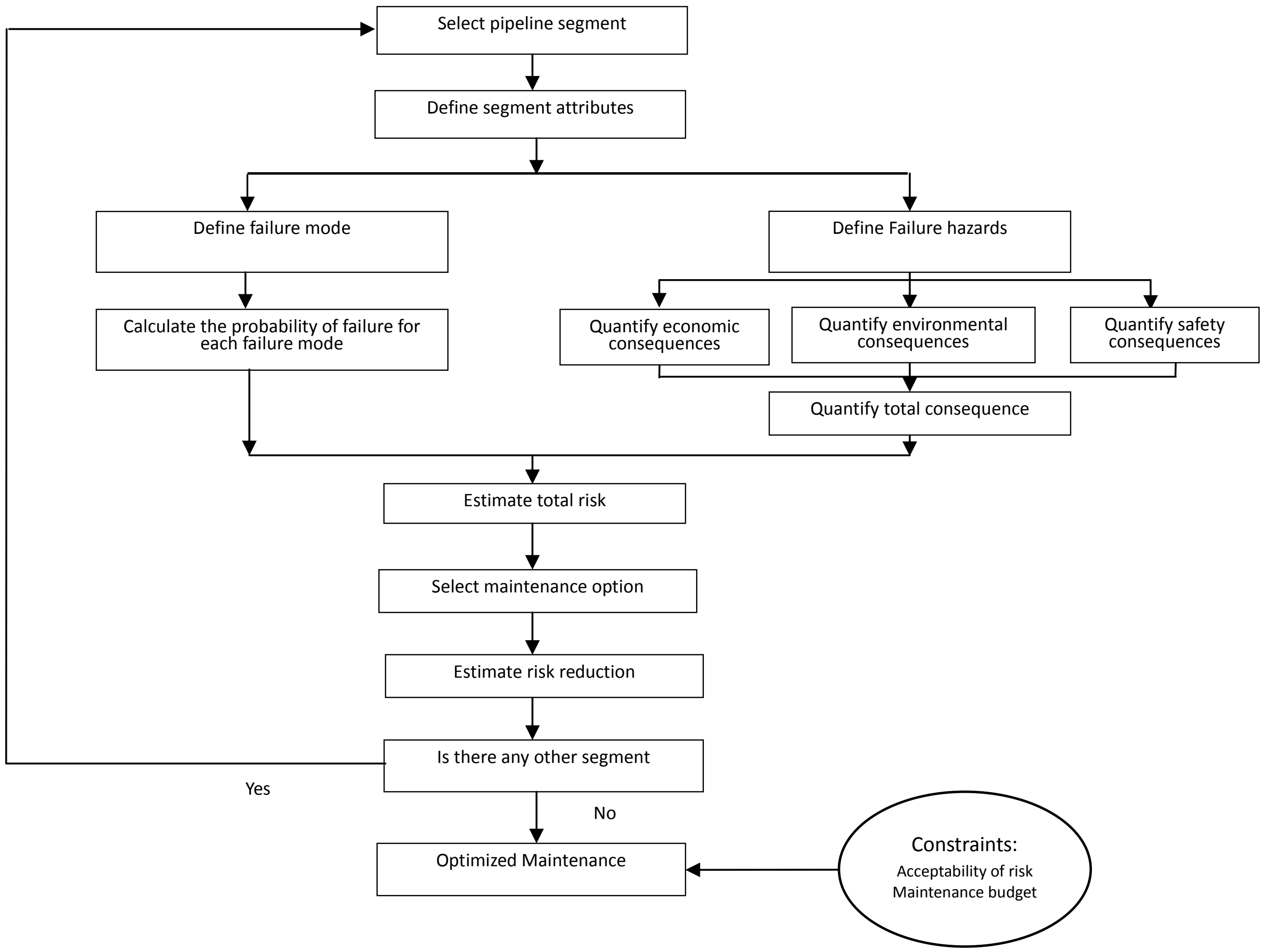

Figure 3

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Figure 4

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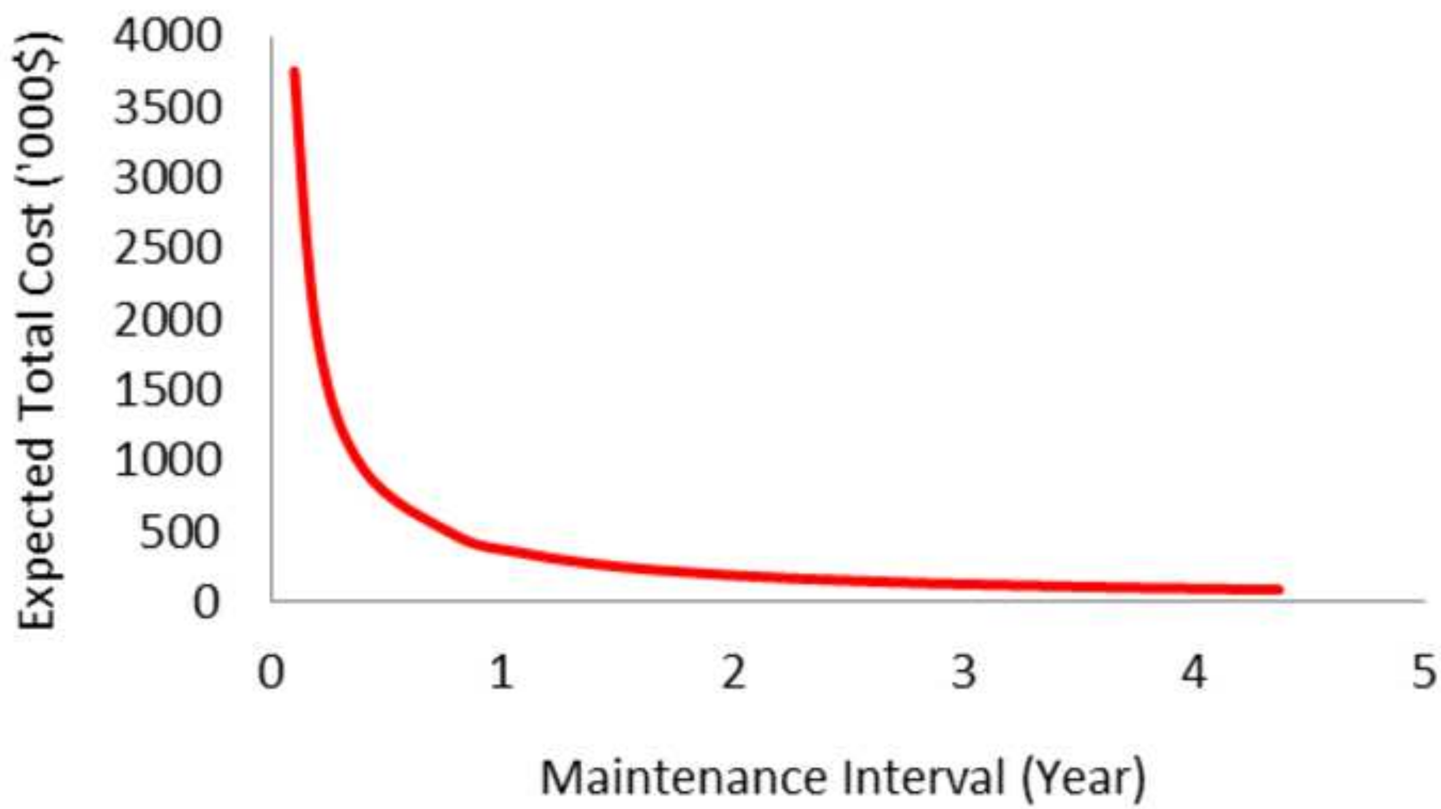

Figure 5

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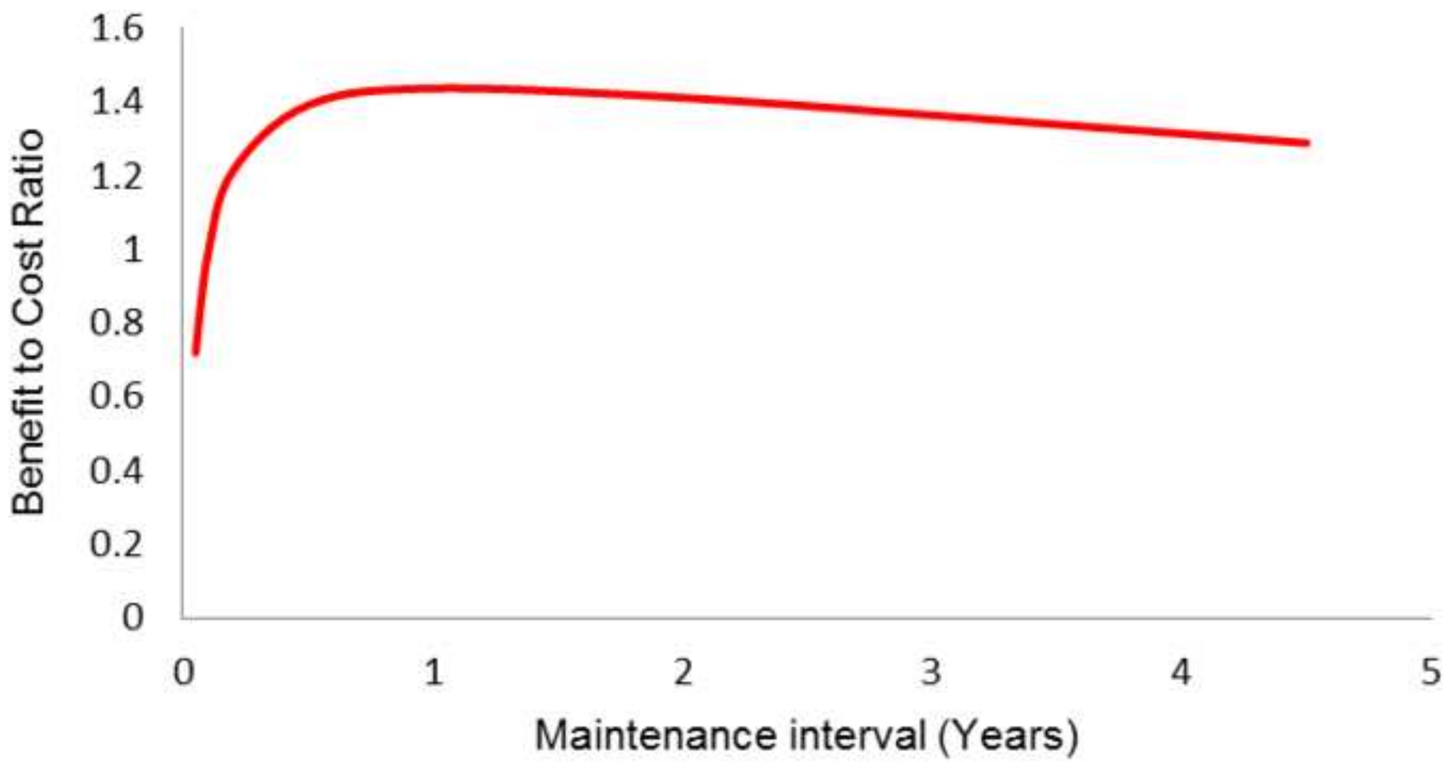
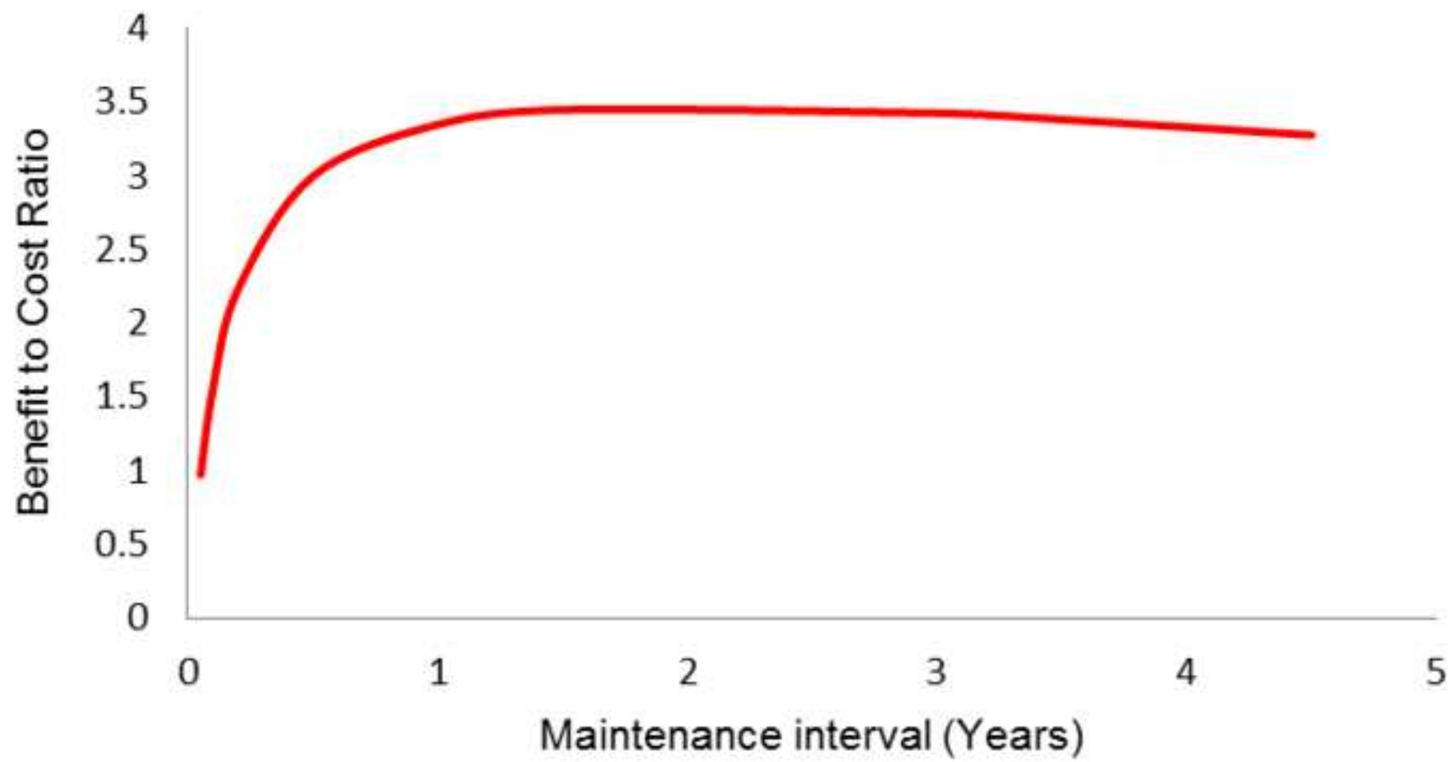


Figure 6

Journal of Pipeline Systems Engineering and Practice. Submitted September 2, 2011; accepted July 13, 2012;
posted ahead of print July 16, 2012. doi:10.1061/(ASCE)PS.1949-1204.0000121



Journal of Pipeline Systems Engineering and Practice. Submitted September 2, 2011; accepted July 13, 2012;
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Table 1: Summary of the attributes of pipeline system

Attribute	Pipeline system in segments		
	PPL 1	PPL 2	PPL 3
Diameter (mm)	406	305	305
Length (km)	1562.2	1526.6	1397.8
Product	Crude	Crude	Crude
Capacity (m^3)	11,300	10,200	5,500
Material	API 5L X42	API 5L X42	API 5L X42
Year	1980	1995	1980
Cathodic protection	Ground bed sacrificial	Ground bed sacrificial	Ground bed sacrificial
External coating	Coaltar enamel	Coaltar enamel	Coaltar enamel

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Table 2: Model parameters for pipeline segments (PPL 1, PPL 2 and PPL 3)

Pipeline	Type of corrosion	Type of failure	Failure parameters	Combined failure rate (*per kmyr*)	Combine MTBF (*yr*)
PPL 1	Uniform Corrosion	NHPP	$\theta = 3.63 \quad \beta = 2.56$	2.93E-03	0.22
	Pitting Corrosion	HPP	1.41E-03		
	Stress Corrosion Cracking	HPP	5.52E-04		
PPL 2	Uniform Corrosion	HPP	1.3E-03	0.79E-03	0.83
	Pitting Corrosion	NHPP	$\theta = 7.08 \quad \beta = 3.65$		
	Stress Corrosion Cracking	HPP	1.21E-04		
PPL 3	Uniform Corrosion	NHPP	$\theta = 2.12 \quad \beta = 1.18$	2.18E-03	0.33
	Pitting Corrosion	HPP	9.70E-04		
	Stress Corrosion Cracking	HPP	1.47E-03		

Journal of Pipeline Systems Engineering and Practice. Submitted September 2, 2011; accepted July 13, 2012;
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Table 3: Sensitivity analysis of preventive maintenance for PPL 1

Uniform Corrosion					
Preventive cost (‘$000)	2,500	6,250	***12,500***	25,000	40,000
Duration (years)	0.75	1.00	***1.25***	1.50	2.00
Expected cost ($million/year)	0.15	0.28	***0.45***	0.70	0.90
Stress Corrosion Cracking					
Preventive cost (‘$000)	2,500	6,250	***12,500***	25,000	40,000
Duration (year)	1.0	1.75	***1.95***	2.25	2.50
Expected cost ($million/year)	1.70	1.30	***1.21***	1.20	1.10
B/C ratio	3.59	3.52	***3.47***	3.39	3.33
Pitting Corrosion					
Preventive cost (‘$000)	2,500	6,250	***12,500***	25,000	40,000
Duration (year)	0.50	1.00	***1.21***	1.30	1.50
Expected cost ($million/year)	3.90	2.70	***2.30***	2.20	2.00
B/C ratio	1.46	1.45	***1.44***	1.43	1.42